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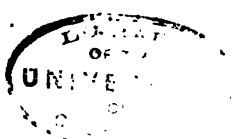
THE STARS

BY

AGNES M. CLERKE

HON. MEMBER OF THE ROYAL ASTRONOMICAL SOCIETY
AUTHOR OF 'HISTORY OF ASTRONOMY DURING THE NINETEENTH CENTURY' AND
'PROBLEMS IN ASTROPHYSICS'



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TO THE MEMORY OF

MY FATHER

JOHN WILLIAM CLERKE

WHO DIED IN LONDON

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PREFACE TO SECOND EDITION

FIFTEEN years have elapsed since the original publication of the present work; and fifteen years count as a long spell of time where sidereal research is in question. In preparing the Second Edition, accordingly, I have introduced extensive modifications. Considerable sections of the book have been recast, and all have been thoroughly revised. New chapters have been inserted, old ones have been in large part suppressed. Drastic measures of reform have, in short, been adopted, with results that certainly import progress and (it is hoped) constitute improvements. Most of the Illustrations are entirely new; and I am under great obligations for the use of valuable photographs and drawings, among others, to Sir David Gill, F.R.S., to Professor Hale and the University Press of Chicago, to the Rev. W. Sidgreaves, S.J., to Professors E. C. Pickering, Campbell, Barnard, and Frost, and to Dr. Max Wolf of Heidelberg.

LONDON, *July* 1905.

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PREFACE TO THE FIRST EDITION

SIDEREAL science has a great future before it. The prospects of its advance are incalculable; the possibilities of its development virtually infinite. No other branch of knowledge attracts efforts for its promotion, at once so wide-spread, so varied, and so enthusiastic; and in no other is anticipation so continually outrun by the brilliant significance of the results achieved.

For the due appreciation, however, of these results, some preliminary knowledge is required, and is possessed by few. To bring it within the reach of many is the object aimed at in the publication of the present volume. Astronomy is essentially a popular science. The general public has an indefeasible right of access to its lofty halls, which it is all the more important to keep cleared of unnecessary technical impediments, that the natural tendency of all sciences is to become specialised as they advance. But literary treatment is the foe of specialisation, and helps to secure, accordingly, the topics it is applied to, against being secluded from the interest and understanding of ordinarily educated men and women. Now, in the whole astonishing history of the human intellect, there is no more astonishing chapter than that concerned with the sidereal researches of the last half century. Nor can the resources of thought be more effectually widened, or its principles be more surely ennobled through the vision of a Higher Wisdom, than by rendering it, so far as possible, intelligible to all.

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The following pages then embody an attempt to combine, in a general survey, some definite particulars of knowledge regarding our sidereal surroundings. The plan pursued has been to instruct by illustrative examples, to select typical instances from each class of phenomena, dwelling upon them with sufficient detail to awaken interest and assist realisation, while avoiding the tediousness inseparable from exhaustive treatment. In developing the subject, it seemed best to proceed from the particular to the general; to start with describing the physical constitution of individual bodies, and ascending by degrees through continually added complexities of mutual relationships, reach at last the crowning problem of the Construction of the Heavens.

The writer gratefully acknowledges the assistance derived, in the preparation of the present work, from the kindness of Sir David Gill, H.M. Astronomer at the Cape, first and chiefly in affording her an opportunity of observing in southern skies; secondly, in reading over several of its chapters in manuscript. Her thanks are also due to Professor E. S. Holden, to Messrs. Burnham, Keeler, and Barnard; to Professor E. C. Pickering, director of Harvard College Observatory; to Sir William and Lady Huggins, Sir Norman Lockyer, Drs. Vogel, Schönfeld, and others for communications of great interest and value.

LONDON, *September* 25, 1890.

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CONTENTS

CHAP.		PAGE
1.	The Task of Sidereal Astronomy	1
2.	The Methods of Sidereal Research	12
3.	The Stars as Suns	34
4.	The Chemistry of Red Stars	49
5.	Gaseous Stars and Nebulæ	58
6.	The Temperatures of the Stars	71
7.	Temporary Stars	81
8.	Stars Variable in Long Periods and Irregularly	97
9.	Variable Stars of Short Period	116
10.	The Colours of the Stars	135
11.	Double Stars	150
12.	Stellar Orbits	162
13.	Variable Double Stars	178
14.	Spectroscopic Binaries	185
15.	Multiple Stars	194
16.	The Evolution of Multiple Stars	208
17.	The Pleiades	215
18.	Star Clusters	227
19.	The Forms of Nebulæ	242
20.	The Great Nebulæ	257
21.	The Nature and Changes of Nebulæ	272
22.	The Distances of the Stars	282
23.	Translation of the Solar System	302
24.	The Proper Motions of the Stars	316
25.	The Milky Way	333
26.	Status of the Nebulæ	349
27.	The Construction of the Heavens	360

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LIST OF ILLUSTRATIONS

PRINTED SEPARATELY

PLATE			
I.	Chart of the Pleiades	*Frontispiece*	
II.	Photographed Stellar Spectra	*To face page*	36
III.	Types of Stellar Spectra	„	44
IV.	Stellar Spectra of Three Types	„	46
V.	Stellar Spectra of the Second, Third, and Fourth Types in the Blue Region	„	56
VI.	Spectrogram of Nova Aurigæ	„	90
VII.	Spectrum of Nova Aurigæ	„	92
VIII.	Spectra of Temporary Stars	„	94
IX.	The Nebulosity round Nova Persei	„	96
X.	Spectrum of Alpha Phœnicis	„	186
XI.	Irregular Star Clusters	„	228
XII.	Photographs of Southern Sidereal Objects	„	238
XIII.	Photographs of Spiral Nebulæ	„	260
XIV.	An Irregular Nebula in Cygnus	„	264
XV.	Photograph of the Looped, or "Spider" Nebula	„	262
XVI.	Photograph of Messier 11 and adjacent Galactic Cloud-forms	„	230
XVII.	Photograph of the Key-Hole Nebula	„	268
XVIII.	The America Nebula	„	270
XIX.	Perforated Galactic Group in Sagittarius	„	338
XX.	The Cocoon Nebula in Cygnus	„	352

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LIST OF ILLUSTRATIONS

PRINTED IN THE TEXT

FIG.		PAGE
1.	Spectrum of Hydrogen in White Stars (Huggins)	38
2.	Distribution of 334 Periods of Variable Stars	98
3.	Two Consecutive Maxima of Mira Ceti	100
4.	Minimum of Mira Ceti, 1902-3	101
5.	Light-Curve of R Normæ	103
6.	Areas of Faculæ on the Sun, 1878-99	104
7.	Light-Curve of U Lupi (Innes)	105
8.	Light-Curve of Eta Carinæ, 1810-1902	108
9.	Curve of Sun-spot Frequency, 1867-77 (Ellis)	113
10.	Distribution of 80 Variable Star Periods under 20^d.	117
11.	Light-Curve of Delta Cephei	118
12.	Typical Light-Curves of Cluster Variables	119
13.	Light-Curve of No. 45 Omega Centauri	120
14.	Light-Curve of S Aræ	120
15.	Light-Curve of U Vulpeculæ	122
16.	Light-Curve of Beta Lyræ (Argelander)	122
17.	Light-Curve of V Puppis	123
18.	Light-Curves of Five Algol Stars	124
19.	System of R^2 Centauri (Roberts)	125
20.	Algol during an Eclipse	129
21.	Minimum of S Cancri	131
22.	Apparent and Real Orbits of Alpha Centauri	164
23.	Four Double Stars photographed at Paris (Mouchez, *Photographie Astronomique*)	166
24.	Orbits of the Component Stars of Gamma Virginis	173
25.	Orbits of the Component Stars of Alpha Centauri	174
26.	Orbits of Sirius and its companion	174
27.	Stars of the Trapezium	206

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FIG. PAGE
28. Plan Sketch of a Nebula (Vogel) 246
29. Helical Nebula in Draco (Holden) 248
30. Spiral Planetary Nebula in Sagitta 248
31. Annular Nebula in Aquarius (Holden) . . . 250
32. Structure-Lines of the Great Nebula in Andromeda . . 258
33. Spiral Structure of the Great Andromeda Nebula . . 259
34. Index Diagram to Structures photographed in the Orion Nebula 266
35. Group of Coronal Structures (W. H. Wesley) . . 267
36. The Earth's Motion in Space (Young) . . . 313
37. The Galactic Spiral (Easton) 344
38. Distribution of 934 Stars within 1° of the Pole, showing the ratio of numbers to space for each half-magnitude . 364

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CHAPTER I

THE TASK OF SIDEREAL ASTRONOMY

WHEN all the stars blaze out on a clear, moonless night, it seems as if it would be impossible to count them; and yet it is seldom that more than 2000 are visible together to the unaided eye. The number, however, depends very much upon climate and sharpness of sight. Argelander enumerated at Bonn, where rather more than eight-tenths of the sphere come successively into view, 3256 stars.[1] But of these no more than 2000 could be, at any one time, above the horizon, and so many would not be *perceptibly* above it, owing to the quenching power of the air in its neighbourhood. Heis, with exceptionally keen sight, distinguished at Münster 1445 more stars than Argelander had seen at Bonn;[2] Houzeau recorded 5719 at Jamaica;[3] Gould 7756 within 100° of the south pole at Cordoba in South America.[4] The discrepancies of these figures are due to the multitude of small stars always, it might be said, hovering on the verge of visibility. If, indeed, the atmosphere could be wholly withdrawn, fully 25,000 stars would, according to a trustworthy estimate, become apparent to moderately good eyes.[5]

Our system of designating the stars has come down to us from a hoar antiquity. It is a very embarrassing one. "The constellations," Sir John Herschel remarks,[6] "seem to have

[1] *Uranometria Nova*, 1843.
[2] Heis, *De Magnitudine Numeroque Stellarum*, p. 16, 1852.
[3] *Uranométrie Générale*, Annales de l'Observatoire de Bruxelles, t. i. 1878.
[4] *Uranometria Argentina*, 1879.
[5] Backhouse, *Journal Liverpool Astr. Society*, vol. vii. p. 226.
[6] *Treatise on Astronomy*, p. 163, *note*.

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been almost purposely named and delineated to cause as much confusion and inconvenience as possible. Innumerable snakes twine through long and contorted areas of the heavens where no memory can follow them; bears, lions, and fishes, large and small, northern and southern, confuse all nomenclature." And yet we could ill afford to dispense with the picturesque associations of a menagerie, largely stocked from the banks of the Euphrates. The signs of the Zodiac, which are undoubtedly of Chaldean origin, embody legendary cycles of thought already, some four thousand years ago, the worse for the wear and dilapidated by time. Homer and Hesiod were familiar with the Bear, Arcturus, and the Dog-star, with "the Hyades, and the Pleiades, and the strength of Orion." The Little Bear was introduced from Phœnicia, when the Pole-star became the mariner's "cynosure." Finally, a number of individual stars have Arabic appellations, dating from the epoch of Saracen supremacy over science. Thus "Vega," the current name of the brightest star in the Greek constellation of the Lyre, is the remnant of an Arabic phrase signifying the "Falling Eagle," while "Altair" stands for the "Flying Eagle;" "Deneb" means the Tail of the Swan; "Fomalhaut," the "Mouth of the Fish;" "Rigel" in Orion is the Leg, "Betelgeux," the "Shoulder of the Giant," and so on.

The constellations[1] now generally recognised are eighty-six in number, of which forty-eight are found in Ptolemy's "Almagest." From Ptolemy, too, is derived the method of classifying the stars by "magnitudes." This is a most inappropriate term, since none of the stars have any perceptible dimensions. They are literally what Shelley calls them, "atoms of intensest light"—globes shrunken by distance to the semblance of mere shining needle-points. Our own sun, removed to the place of the nearest fixed star, would be in the same condition; contracted to $\frac{1}{143}''$, its diameter would be utterly inappreciable with the largest telescope. It is true that the telescopic images of the stars appear to be of measurable size; but this is a purely optical effect, and the "spurious discs" shown by them actually grow

[1] For an easy method of identifying the chief northern stars, see Sir Robert Ball's *Story of the Heavens*, p. 372; also the "Uranography" in Young's *Elements of Astronomy*, 1890.

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smaller instead of larger as the power of the instrument is increased.

"Magnitude" has, then, nothing to do with apparent size, but refers entirely to apparent lustre, which depends upon distance and intensity of shining, as well as upon actual dimensions. The faintest stars have the highest numerical magnitudes; and it has been found that the gap between each successive order, as represented by the stars traditionally belonging to it, corresponds to a falling-off of light in the proportion of about $2\frac{1}{2}$ to 1. The arrangement by magnitudes is, of course, entirely arbitrary; natural gradations are not by a flight of steps, but along an inclined plane. Stars classed as of the first magnitude (of which there are ten in each hemisphere)[1] differ accordingly very much among themselves. Sirius exceeds Regulus no less than fourteen and a half times; Vega is more than twice as brilliant as Aldebaran. Vega, Capella, and Arcturus hold a co-ordinate primacy in the northern hemisphere, but are outshone in the southern by Sirius, Canopus, and *a* Centauri. Of second magnitude are the seven stars grouped to form "Charles's Wain," the Pole-star, and some of the most vivid gems in Perseus, Cassiopeia, and the Swan. Stars of the sixth magnitude are the faintest ordinarily visible to the naked eye; but those of the seventh can be seen under advantageous circumstances. The plan, introduced by Bayer in 1603, of naming the stars of the several constellations roughly in order of brightness by the letters of the Greek alphabet, established for each a kind of light-sequence, useful, though far from exact. The smaller stars are usually distinguished by the numbers attached to them in various catalogues.

One of the most notorious circumstances about the stars is their "twinkling." They undergo, especially when near the horizon, extremely rapid changes of lustre, attended sometimes by the glinting of prismatic colours. Nor do all stand, in this respect, on the same level. White stars twinkle more than red ones. Even early and untutored observers noticed how

> The fiery Sirius alters hue,
> And bickers into red and emerald.

[1] See Appendix, Table I.

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whence it was called by Aratus ποικίλος, the "many-coloured"; and chromatic unsteadiness was a marked peculiarity of the "new stars" of 1572 and 1604.

It is easy to see that this effect is in some way due to the atmosphere. Like refraction, it vanishes at the zenith; it varies in intensity with weather and climate. The first rational conjecture as to its cause was made in 1667 by Robert Hooke, who attributed it to irregular refraction in the various air-strata. More exact inquiries on the subject have, in recent times, led to some curious results.

The impressions of light on the retina last, according to Plateau's careful determination, 0·34—say one-third—of a second. This is the limit of their individual perceptibility. With more frequent recurrence, they become merged indistinguishably together. But the changes producing scintillation succeed each other much more rapidly than three times in a second. Hence the need of some means of separating and analysing them.

These were provided by M. Montigny's "scintillometer,"[1] in which the sensibility of different parts of the retina was skilfully turned to account for the registration of a swift succession of impressions. By the rotation of a glass-plate obliquely inserted in front of the eye-piece of a refracting telescope, the image of a star viewed with it is made to describe an exact circle in the field. The line of light traced out is, in perfectly steady air, continuous and of a uniform hue, but breaks up, under the influence of scintillation, into vividly tinted arcs, at times into prismatic "pearls." The addition of a pair of crossed wires facilitates the reckoning of the colour-fluctuations thus rendered separately visible; and they are found to occur, on an average, in white stars standing thirty degrees above the horizon, seventy-eight times in a second, in yellow and red stars similarly placed, sixty-eight and fifty-six times respectively.[2]

The explanation of these appearances is evidently to be sought in the refractive power, combined with the turbulence

[1] Described in *Bulletin de l'Acad. des Sciences*, Bruxelles, t. xvii. p. 261, 2nd series; *Monthly Notices*, vol. xxxvii. p. 208; *Ciel et Terre* (Fievez), t. i. p. 369.

[2] *Bull. de l'Acad.* Bruxelles, t. xxxvii. p. 185, 2nd series.

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of our aerial envelope. For a different path through its strata is necessarily pursued by each of the differently refrangible beams united to form the image of a star. The violet enters them higher up, since it is more bent in transit than the red; and so proportionately of the rest. Each then is liable to encounter different vicissitudes on the way, betrayed to our sight by rapid flashes of colour. Each is affected by innumerable small deviations and momentary caprices of refraction; so that the bundle of rays picturing a star at a given instant is, as it were, a fortuitous and eminently unstable combination. It is dissolved, and a new one constituted, sixty or seventy times in a second; and the elements temporarily missing determine the resulting tint. The fundamental fact of the matter, in short, is that the light of every star near the horizon is drawn out into a tiny spectrum by the chromatic dispersion of the atmosphere; and Respighi's study of the fluctuations in these prismatic images[1] provided, accordingly, the first secure basis for a scientific theory of scintillation.

That white twinkle more than red stars becomes intelligible when we consider that the sheaf of their beams being fuller, interceptions of them are more frequent. But planets which are radiating *discs*, and not merely *points*, rarely show the effect, because the absence of rays from one part is compensated by the arrival of rays from other parts of their surfaces. Similarly, the steady radiance of stars in large telescopes is due to the neutralisation of each casual stoppage by the great number of the beams collected together. Instead of a twinkling image, however, a blurred and distended one is formed under perturbed conditions, and observation gains nothing by the exchange. And since the degree to which this phenomenon is present varies very much with locality, regard should be had to its prevalence in choosing[2] sites for powerful instruments. It diminishes, on the whole, with altitude, but the configuration of adjacent mountain-ranges is strongly influential, and Dr. Pernter found Sirius actually to scintillate

[1] *Les Mondes*, t. xix. p. 698 (1869); Lord Rayleigh, *Phil. Mag.* vol. xxxvi. p. 129, 1903.

[2] Exner, *Astr. Nach.* No. 2791; A. E. Douglass, *Popular Astronomy*, June 1897; Lowell, *Monthly Notices*, vol. lxiii. p. 40; Exner and Villiger, *Astroph. Journ.* vol. xxi. p. 368.

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more at the summit than at the foot of the Sonnblick (10,000 feet high).[1]

Scintillation, like astronomical refraction, augments as the thermometer falls and as the barometer rises. This is inevitable, since the first requisite for its occurrence is differential refractive action on the various light-rays.[2] But it has other less obviously accountable meteorological relations. M. Montigny ascertained, by the experience of nearly forty years, that with the quantity of moisture in the air the twinkling of the stars increases so markedly as to serve for a useful prognostic of rain. Cyclonic conditions promote it;[3] and it is extremely sensitive to magnetic disturbances.[4] Ussher was struck, in the eighteenth century, with the surprising vividness of scintillation during auroræ; Montigny extended the coincidence to magnetic commotions perceptible only instrumentally. Moreover, Weber remarked at Peckeloh in 1880, that stars situated near the magnetic meridian twinkled more than elsewhere in the sky;[5] and although little attention has of late been paid to the possible dependence of the effect upon the points of the compass, yet the theoretical interest of scintillation would be much enhanced should it turn out to be one of the many terrestrial phenomena associated with vicissitudes in the physical condition of the sun.

The world of stars thrown open by the telescope may fairly be called boundless. Using a glass only two and a half inches across, Argelander registered 324,189 down to $9\frac{1}{2}$ magnitude, all in the northern hemisphere, with the addition of a southern zone one degree wide. The work was extended to the southern tropic by Schönfeld, and completed to the southern pole under Sir David Gill's direction. At the Cape, the photographic method was employed, and the resulting enrolment, published 1896-1900, comprises 454,875 stars nearly to the tenth magnitude; while the Cordoba visual Durchmusterung, executed by Thome and Tucker, 1885-1904, is a still more comprehensive register of southern objects. Yet

[1] *Observatory*, vol. xii. p. 194.
[2] Montigny, *Bull. de l'Acad.* Bruxelles, t. xlvi. p. 613, 2nd series.
[3] Rosenthal, *Meteor. Zeitschrift*, Bd. xx. p. 145.
[4] *Comptes Rendus*, t. xcvi. p. 573.
[5] *Wochenschrift für Astronomie*, 1880, p. 294.

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these great works are merely preliminary to the International charting operations in progress. Their accomplishment will yield a "Catalogue of precision" including at least three million stars; and somewhere about thirty millions, taken from the submerged population of space, will, by their record on the chart-plates, be admitted to the citizenship of astronomy. They can never thenceforward be excluded from the scope of research. Their light-changes, their movements, their distribution, will present an inexhaustible, and probably a most fruitful field of inquiry.

Mr. Plummer showed in 1877[1] that the lucid stars (those visible to the naked eye) in the Bonn Durchmusterung give as much light as 7349, the telescopic stars as 23,337 sixth magnitude stars. Those singly imperceptible thus really illuminate the sky just three times more than those individually seen. Summing up, with the aid of the best photometric data, the entire light of Argelander's 324,000 stars, we get for its equivalent $\frac{1}{440}$ full moonlight; and we may roughly estimate the total light of all those similarly enumerated in both hemispheres, to the number of about 900,000, at $\frac{1}{180}$ the lunar brightness. The amount of scattered effulgence dispensed by still fainter stars is exceedingly difficult to evaluate. Sir William Abney, using a photographic method, rated in 1896 the sum of starlight in both hemispheres at $\frac{1}{100}$ full moonlight. Professor Newcomb, in 1901,[2] from visual observations of diffused sky-radiance, concluded the light-power of all the stars to be just 728 times that of Capella;[3] and 728 stars like Capella give $\frac{1}{89}$ the light of the full moon.[4] But it is far from certain that the vault of heaven would seem absolutely black if the stars were blotted out.[5] Our upper air is the seat of processes by which luminosity is at times strongly developed; and we cannot be sure that they are ever entirely suspended. Hence, Professor Newcomb's experiments afford no assurance regarding the

[1] *Monthly Notices*, vol. xxxvii. p. 436.

[2] *Astrophysical Journal*, vol. xiv. p. 310; see also Gavin J. Burns, *ibid.* vol. xvi. p. 166.

[3] Newcomb's 600 stars of 0·0 magnitude are equal to 728 of the photometric brightness (0·21) of Capella.

[4] Müller, *Photometrie der Gestirne*, p. 340.

[5] Cf. Burns, *Journ. Brit. Astr. Ass.* vol. xv. p. 91.

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equivalent, to say nothing of the actual number of stars coming directly, or indirectly within our ken. These last cannot well fall short of sixty millions, and they more probably sum up to one hundred millions; but the nets of inquiry can at present scarcely be drawn closer. Yet the fact is noteworthy that each class of stars sends us appreciably more light than the class next above it. The light-aggregate of second magnitude stars exceeds that of first, of third that of second, and so on. The fainter the stars, in short, the greater is their total luminous power,[1] because their augmented numbers more than counterbalance their diminished individual lustre. But this progression, it is evident, cannot go on indefinitely, since otherwise an indefinitely intense radiance would fill the sky. Darkness would be abolished through the shining of invisible stars. It follows either that the observed order of the stellar world has assignable limits—that the star-depths, however profound, are not absolutely unfathomable; or that space, for whatever reason, is not absolutely transparent.

The task of exploration, at any rate, does not seem to be altogether hopeless. It can never indeed be exhausted; but it can fairly be grappled with by finite minds. It does not evade their efforts with the passive scorn of material infinitude. Genuine, if partial, successes have crowned them in the past, and will, it may be hoped, continue to crown them in the future.

We must not, however, in seeking encouragement from the thought that it does not utterly defy our powers, underrate the difficulty of the enterprise we have taken in hand. The nature of our own sun offers a vast and intricate problem, still very far from being solved; but stellar space contains many millions of suns, variously constituted, variously circumstanced, frequently surpassing our magnificent orb in size and splendour. Now each of these millions of suns challenges the closest *personal* attention; no single one of them is exactly like any other, and their differences and resemblances open endless vistas of instruction and interest. Their inconceivable remoteness in no way derogates from their real dignity. An all but evanescent speck of light in the field of the great Lick refractor may be the life-giving centre of a

[1] *L'Astronomie*, t. v. p. 409.

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system of worlds, each abounding as marvellously with proofs of creative wisdom and goodness as the little planet in which our temporal destinies are imprisoned. Such light-specks are then equally deserving of study with the most effulgent orbs in the sky, although it may never be practicable to bestow it upon them. We can indeed hardly imagine the amount of telescopic improvement which would be needed in order to bring them within the range of critical examination. For the present, accordingly, physical research must be confined to some thousands of the brighter stars which may serve as specimens of the rest. Nor need we lament the restriction. Generations of workers might expend their energies in gathering facts from the field actually open to them, and yet leave a full harvest for their successors. In all experimental inquiries, it may with truth be said that the reaper, as he garners one crop of knowledge, sows another: so endless are the secrets of nature, so untiring the inquisitiveness of man.

The stars in their combinations demand inquiry no less than the stars in themselves. Stellar systems are to be met with in indescribable profusion and variety, from mutually circling pairs, through groups including thousands of physically related objects, to the stupendous integrated collection which we call the Milky Way. But as yet investigation has barely skirted the edge of this well-nigh infinite region. Before it can be penetrated by so much as a plausible conjecture, statistics are wanted of the distances and movements of thousands, nay millions of stars.

Nor is the amassing of them any longer the Sisyphean labour it seemed a short time since. By the unhoped-for development of novel methods, the pace of inquiry has been quickened all along the line. Particulars are accumulated faster than they can be assorted and arranged. Time has virtually expanded, as if for the purpose of gratifying curiosity which becomes keener as its sublime objects loom more distinctly above the horizon of thought. Ten years now count for a century of the old plodding advance. Express trains carry passengers on errands of research, as well as of business or pleasure. Problems ripen as if in a forcing-house, and so numerously as almost to bewilder the attention.

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The whole subject of sidereal natural history is wide and intricate beyond what it is easy to convey to those approaching it for the first time. There is scarcely a topic in physical astronomy with which it is unconnected. The progress of discovery has gradually drawn closer the generic relationships of the heavenly bodies. The sun has come to be recognised as the grand exemplar of the stars; meteorites show themselves to be intimately associated with comets; comets are perhaps the shreds of used-up nebulæ; while the stellar and nebular realms blend one with the other as indistinguishably as the animal and vegetable kingdoms of organic nature.

The strange cloud-like objects called "nebulæ" may be considered as wholly of telescopic revelation. Only one of them—the famous object in the girdle of Andromeda—can be at all easily seen with the naked eye; and even that escaped the notice of all the Greek, and most of the mediæval astronomers. The "nebulosæ" of the ancients were many of them small groups of stars accidentally set close together; but among the seven enumerated by Ptolemy were two real clusters like the Pleiades, only (presumably) much farther away, one in Perseus, and the other in Cancer. Indeed, to extremely short-sighted persons, the Pleiades themselves put on a nebulous appearance, the individual stars running together into one wide blot of light.

Halley was the first to form anything like an adequate conception of the importance of nebular observations. He was acquainted in 1716 with six "luminous spots or patches, which discover themselves only by the telescope, and appear to the naked eye like small fixed stars; but in reality are nothing else but the light coming from an extraordinary great space in the ether, through which a lucid medium is diffused, that shines with its own proper lustre."[1] Only two of Halley's half-dozen objects, however—those in Orion and Andromeda—were genuine nebulæ; the rest when viewed with better instruments than his "six-foot tube," proved to be magnificent star clusters.

This small beginning of knowledge was followed up by Lacaille in the southern, by Messier in the northern hemi-

[1] *Phil. Trans.* vol. xxix. p. 390.

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sphere. Then Herschel's great telescopes opened the modern epoch in the science of nebulæ. As the result of his labours they came to be reckoned by the thousand instead of by the score. Portions of the sky were found to be crowded with them. Yet the vast majority must always, owing to their extreme faintness, remain imperceptible without powerful optical aid, only sixty-four coming into view with the same telescope which showed Argelander 324,000 stars. Thus access to the nebular heavens can be gained only by making the very most of the little light they send us. Large telescopes and prolonged photographic exposures are indeed pre-eminently useful in this department of celestial physics, which, mainly through the application of the camera, has of late incalculably widened. A pioneering survey with the Crossley reflector led Professor Keeler to estimate at 120,000 the number of nebulæ which might be chemically recorded by its means; and the specimen sheaves garnered by Dr. Max Wolf at Königstuhl in 1901 are no less promising for a rich future harvest. But discoveries are of small account if succeeded by neglect. Assiduous and prolonged observation is indispensable for the detection of the cyclical or progressive changes doubtless proceeding in these inchoate systems.

This then is the task of sidereal astronomy—to investigate the nature, origin, and relationships of 30,000,000 stars and of 120,000 nebulæ—to inquire into their movements among themselves, and that of our sun among them—to assign to each its place and rank in the universal order, and, gathering hints of what has been and what will be from what is, distinguish hierarchies of celestial systems, and thus at last rise to the higher synthesis embracing the grand mechanism of the entire—the sublime idea of Omnipotence, to which the stars conform their courses, while "they shine forth with joy to Him that made them."

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CHAPTER II

THE METHODS OF SIDEREAL RESEARCH

SIDEREAL science is, on its geometrical side, of modern development; on its physical side, of modern origin. The places of the stars, as referred to certain lines and points on the surface of an imaginary hollow sphere, are obtained now on essentially the same principles as by Hipparchus, only with incomparably greater refinement. And refinement is everything where the stars are concerned. Significant changes among them can only be brought out by minute accuracy. To a rough discernment their relative situations are immutable; and systematic inquiries into their movements hence became possible only when the grosser errors were banished from observation. Bessel's discovery of Bradley's exactitude gave the signal for such inquiries. It seemed worth while to re-observe stars already so well determined that discrepancies might safely be interpreted to mean real change.

Thus it is only within the last hundred years that the stars have been extensively catalogued for their own sakes and no longer in subordination to the interests of planetary or cometary astronomy. The scope of such labours now widens continually. For the objects of them are all but innumerable, and the inception of ambitious schemes is encouraged by modern facilities for executing them by combination. The project set on foot by the German Astronomical Society in 1865 of fixing the precise places of stars to the ninth magnitude, found co-operators in all parts of the world; and its virtual completion in 1903 to the verge of the southern zones observed by Gould and Gilliss, raised the number of stars not merely recorded, but known in the strict astrometrical sense, to not far from 400,000.

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A star is located in the heavens, just as a city or a mountain is located on the earth, by measurements along two imaginary circles. Its "declination," or distance from the celestial equator, corresponds to terrestrial latitude; its "right ascension" to terrestrial longitude. The astronomical prime meridian passes through the first point of Aries, that is, the sun's position at the vernal equinox; intervals from it are reckoned eastward from 0° to 360°, or in time from 0^h to 24^h. And since the zero-point retreats slowly westward by the effect of precession, it follows that the right ascensions of most stars increase steadily year by year, apart from any movements "proper" to themselves.

The diurnal revolution of the sphere furnishes the sole standard of time in sidereal astronomy. Sidereal noon at a given locality is the moment when the first point of Aries crosses the meridian of that spot; the right ascensions of the heavenly bodies indicating the order of their successive culminations. Thus, if the right ascension of a star be two hours and twelve minutes, it will cross the meridian of any place on the earth two hours and twelve minutes after the first point of Aries has crossed it, *coming up behind it*, to that extent, in the grand diurnal procession. Differences in right ascension signify differences in times of culmination; and their measures in hours, minutes, and seconds need only multiplication by fifteen (the number of times that 24 is contained in 360), to appear as measures of arc in degrees, minutes, and seconds.

A transit-circle and a clock are the two essential instruments for ascertaining the places of the stars. The instant, to the tenth of a second, at which a star stands in the meridian, is noted; the vertical circle is read, showing its "zenith-distance" (giving at once its declination when the latitude of the observatory is known), and the observational part of the work is done. The data thus obtained, after undergoing numerous corrections, suffice to determine the position of the star with reference to some other "fundamental" star, the *absolute* place of which has been separately and laboriously ascertained.

This business of star-location forms the substratum of the older astronomy. But the precision given to it is altogether

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new, and alone has fitted it to be the means of eliciting facts so coy as those that relate to stellar movements. For their disclosure devices of accuracy are needed which our astronomical progenitors never cast a thought upon. Optical and mechanical skill has, in our days, reached a point of almost ideal perfection; yet when the artist has done his utmost, the instrument is, in a sense, still in the rough. The astronomer then takes it in hand, and his part is often the more arduous and anxious. The investigation of small surviving errors, the contrivance of methods for neutralising their effects, the carrying out of delicate operations of adjustment, the detection of microscopic deformations, tremors of the soil, inequalities of expansion by heat, fall to his share. Even his own rate of sense-transmission has to be measured, and figures, under the title of "personal equation," as a correction in the final result. For, between the actual occurrence and the perception of a phenomenon, there is always a gap, more or less wide, according to individual idiosyncrasy, and it is only after this gap—tiny though it be—has been crossed, that electricity can be called upon to play its prompt part as amanuensis to the observer.

This detailed and painful struggle against error has made sidereal astronomy possible, by *precipitating* from the mixed solution that held them the minute quantities it deals with. Just because the universe is almost infinitely large, these quantities are almost infinitely small. They are small, not in themselves, but through the incomprehensible remoteness of the bodies they affect.

Sidereal astronomy is deeply concerned with the motions of the stars. These are of different kinds. "Proper" motions —so-called to distinguish them from "common" apparent displacements due to the slow shifting of the points of reference on the sphere—advance uniformly along a great circle; orbital revolutions of one star round another are periodical in small ellipses; besides which annual oscillations, varying in extent with the distances from ourselves of the objects performing them, are barely measurable in a few of the nearest stars. The perception and characterisation of these orbital and "parallactic" movements have become possible only through the attainment of exquisite observational accuracy.

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The instruments employed are the equatoreal with micrometer attached, and the heliometer.

An equatoreal is a telescope so mounted as to follow the diurnal revolution of the heavens. It is connected with an axis directed towards the pole, and revolving by clockwork once in twenty-four hours. An object accordingly once brought into its field of view remains there immovably for any desired time, provided the tube be clamped in position, and the clock set going. The inconvenience of the earth's rotation in producing a continual "march-past" of the heavenly bodies is thus neutralised.

To the eye-end of an equatoreal is usually attached an arrangement of spider lines constituting a "filar micrometer." Two sets of such threads (which in subtlety and evenness of texture far surpass any artificial product), crossing at right angles and some of them movable by fine screws, while the whole can be made to revolve together, afford a most delicate means of ascertaining the distance and direction from each other of any two objects close enough for simultaneous observation. Measures of double stars are executed, and some stellar parallaxes have been determined in this way. But for the latter purpose, the "heliometer" is the more appropriate instrument.

Its designation is a misnomer, or rather represents the tradition of an original purpose to which it was never effectively applied. The true function of a heliometer is the critical measurement of two adjacent stars, or of a star and planet. Primarily, it is an equatoreal telescope; its micrometrical powers are conferred by the division of the object-glass into two halves sliding along their common diameter, and duplicating by their separation the combined image formed by them when together. The amount of movement given to the segments in bringing about alternate coincidences between opposite members of the pair of stars shown by each, suffices to determine with the utmost nicety the interval between them. That is to say, after endless precautions for accuracy have been taken, and endless care bestowed upon detecting and obviating occasions of infinitesimal error.

The Radcliffe Observatory at Oxford possesses the largest heliometer in existence. The diameter of its object-glass is

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seven and a half inches. A similar instrument, however, erected at the Royal Observatory, Cape of Good Hope, nearly forty years later, is but slightly inferior in size, and is in other respects considerably its superior. Dr. Elkin, at Yale College, has charge of the only heliometer in the New World, while a good many are to be found in Germany and Russia. The Repsolds of Hamburg may be said to hold a monopoly in the mechanical part of their production; and Merz of Munich stands almost alone among opticians in his readiness to take the responsibility of sawing a fine object-glass in two. Nor is the aptitude for the use of these instruments by any means universal among observers; hence their comparative scarcity.

The science of the *motions* of the stars is only a part of modern sidereal astronomy. Within the last forty years a science of their *nature* has in defiance of forecast sprung up, and assumed surprising proportions. Sidereal physics has a great future in store for it. Its expansiveness in all directions is positively bewildering. The "What next?" is hardly asked, when it is answered, and often in the least looked-for manner. In following its progress, the mind becomes so inured to novelties, that antecedent improbability ceases to suggest dissent. Some details of what we have thus so far learnt will be contained in the ensuing chapters; the means employed must be briefly indicated in this.

They are of three principal kinds—spectroscopic, photometric, and photographic. The general theory of spectrum analysis has been explained elsewhere;[1] here we need only repeat that it rests upon the constancy of the positions in the spectrum belonging to the rays of light given out by ignited vapours. These invariable lines serve as an index to the presence in the sun or in a star, no less than in the laboratory, of the substance they are associated with. Whether they be bright or dark, the principle remains the same. They are bright when the vapour originating them is the chief source of illumination; dark, when a stronger light coming from behind is absorbed by its interposition. Their appearance as "lines" is merely due to the transmission through a narrow slit of the light afterwards prismatically dispersed.

[1] See the author's *History of Astronomy*, 4th edit. p. 139.

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Now a main difficulty in getting starlight to disclose its secrets, is that there is so little of it. It will not bear the necessary amount of spreading-out, but evades analysis by fading into imperceptibility, like a runnel of water that widens only to disappear. Hence the absolute necessity in stellar spectroscopy for large telescopes. The collecting nets have to be widely extended to gather in a commodity so scarce. Could we at all realise, indeed, the portentous expanse of the ever-broadening sphere filled by the stellar beams as they travel towards us, we should be inclined to wonder, not at their faintness, but at their intensity. But the weakening effect of distance is in some degree counteracted by powerful concentration; and this is one of the chief uses of the large telescopic apertures so much in vogue at the present time.

Viewed with the Lick refractor of 36 inches, any given star is 32,400 times brighter than it appears to the naked eye, or 324 times brighter than when shown by a 2-inch telescope.[1] The large instrument, that is to say, provides 324 times more material for experimenting upon, or ranges further by $6\frac{1}{4}$ stellar magnitudes than the small refractor.

The interpretation of spectral hieroglyphics, by which we learn the chemical constitution of a star, is a very delicate and laborious operation. What is called a "comparison-spectrum" is usually employed as an adjunct to it. Rays from some terrestrial source are reflected into one half of the slit, through the other half of which the stellar rays are admitted. Both sets then traverse the same prisms, and form strictly comparable spectra side by side in the same field of view. Lines common to both can thus easily be identified; and their genuine occurrence leaves no doubt that the element compared—hydrogen, sodium, iron, magnesium, or any other—enters into the composition of the star. But this process of matching can seldom or never be completely carried out. A dozen known lines may be attended by a hundred unknown ones, either too faint to be distinctly seen, or in positions unfamiliar to terrestrial light-chemistry. Nor is it safe to infer the absence of an ingredient from the absence of its representative rays. Many causes contribute to render the display of lines in stellar spectra selective.

[1] Holden, *English Mechanic*, vol. xlvi. p. 528.

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Where direct comparisons can be dispensed with, a slit is not essential to stellar light-analysis. For a star, having no sensible dimensions, gives rise to none of the confused overlaying of images produced by grosser light-sources unless superfluous rays be excluded by the use of a fine linear aperture. Hence the possibility of applying a "slitless spectroscope" to the stars. Their light is then simply passed through a prism, either before it enters, or as it leaves the telescope. The resulting variegated stripe, looked at through a cylindrical lens to give it some tangible breadth, shows the dark gaps or lines significant of the "type" of the star.

But prismatic analysis is not merely communicative as to the physical and chemical nature of the stars. It can tell something of their movements as well. And, what is especially fortunate, the information that it gives is of a kind otherwise inaccessible. "End-on" motions, as every one knows, are visually imperceptible; the discovery that the spectroscope has the power to make them sensible is of such far-reaching importance that Sir William Huggins, by bringing the method into effective operation, performed perhaps the greatest of his many services to science. Through the link thus established, geometrical and physical astronomy have been placed in closer mutual relations than could have been thought possible beforehand.

The observations concerned are of great delicacy, and can only be made with a powerful telescope, collecting light sufficient to bear a considerable amount of dispersion. Their object is to measure the minute displacements of known lines due to "radial" or end-on motion, and proportional in amount to its velocity. These displacements are towards the blue end of the spectrum when the star is approaching, towards the red when it is receding from the earth. The refrangibility of the luminous beams is changed, in the one case, by the crowding together of the ethereal vibrations, rendering them more numerous in a given time, in the other, by their being (as it were) drawn apart, and so rendered less numerous. The juxtaposition of a standard terrestrial spectrum, such as that of iron, gives the means of measuring deviations thus produced, and so of determining the rate of approach or recession of the star examined. But the process is impeded to a

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degree hardly imaginable without personal experience by troubles in the ocean of our air. The twinkling of the stars is represented in their spectra by tremors and undulations often permitting only instantaneous estimates of line-positions. This inconvenience has been largely remedied by the use of the camera.

Stellar photometry has a twofold object. It gives the means of investigating, first, the individual nature; secondly, the collective relations of the stars. Stellar lustre is affected by endless gradations of change. It is rarely, perhaps never, really constant. Periodical fluctuations are in many cases obvious; secular variations are suspected. The suspicion can be verified only by precise light-measurements repeated at long intervals.

Their application to the problems of stellar distribution becomes feasible through the dependence of brightness upon distance. The law of the *decrease* of light with the *increase* of the square of the distance is universally familiar. If all the stars were equal in themselves, their apparent differences would thus at once disclose their relative remoteness. We could locate them in space just as accurately as we could determine their lustre. But in point of fact the stars are vastly diversified in size and luminosity, and we can hence reason from distance to brightness only by wide averages. A statistical method alone is available, and its employment involves the establishment of strict principles of light-measurement.

The first requisite for this purpose was an unvarying and consistent scale, which was provided with the least possible disturbance to existing habits of thought by regularising the antique mode of estimation by "magnitudes." Intervals loosely defined and unequal were made precise. A "light ratio" was agreed upon. To this proportion of change from one magnitude to the next, the numerical value 2·512[1] has been assigned. That is to say, an average first magnitude star sends us 2·512 times as much light as an average star of the second magnitude, which, in its turn, is 2·512 times brighter than one of the third, and so on. From the first to the third magnitude, the step is evidently measured by the

[1] Selected as the number of which 0·4 is the logarithm.

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square of the "light ratio" ($2{\cdot}512 \times 2{\cdot}512 = 6{\cdot}310$); and in general the relative brilliancy of any two stars may be found by raising 2·512 to a power represented by the numerical difference of their magnitudes. One first magnitude star, for instance, is equivalent to one hundred of the sixth rank ($(2{\cdot}512)^5 = 100$); and to no less than a million stars of the sixteenth magnitude.

All this is a matter of pure definition, and definition is a useful leading-string to experiment. It is something to have a clear conception in the abstract of what a tenth, eleventh, twentieth magnitude star is, even though the conception be not altogether easy to realise. The problem of applying the numerical standard set up was practically solved almost at the same time by Professor Pritchard at Oxford, and by Professor Pickering at Cambridge in the United States. They first systematically and extensively employed instrumental means in stellar photometry, with the result of satisfactorily ascertaining the comparative lustre of all stars visible to the naked eye in these latitudes.

Professor Pritchard adopted for his researches the "method of extinctions." The image of each star was made to vanish by sliding between it and the eye a wedge of neutral-tinted glass, of which the thickness just needed to produce invisibility, was found to give a very exact measure of intensity. In this way the brightness of 2784 stars from the pole to ten degrees south of the equator was determined and registered in the "Uranometria Nova Oxoniensis."

The Harvard "meridian-photometer" was constructed on the principle of "equalisation." The images of the pole-star (adopted as a standard of comparison) and of each star successively experimented upon were reflected into a fixed telescope, and brought to an exact equality by means of a polarising apparatus. From the amount of rotation given, for this purpose, to the double refracting prism, the actual difference of brightness was easily deduced. The method is of wider applicability than that by extinctions; none the less, the "wedge photometer," in the form given to it by Pritchard, has taken its place as an indispensable adjunct to such inquiries. With either instrument the limit of clearly distinguishable difference is about one-tenth of a magnitude.

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The original Harvard photometry[1] included all stars to the sixth magnitude as far as 30° of south latitude, to the number of 4260. But it was only the first in a series of similar and larger works. Its extension over the entire heavens was accomplished by the publication in 1895 of the Southern Harvard Photometry of 7922 stars;[2] and the Revised Harvard Photometry, embracing about 9000 stars in both hemispheres, was approaching completion in 1903.[3] A Photometric Durchmusterung of stars to 7·5 magnitude within 130° of the North Pole was besides constructed with a larger instrument,[4] while the measurement of thousands of stars in zones has established standards of exact comparison down to the ninth stellar magnitude.

Potsdam is also the scene of extensive photometric operations, which have now virtually reached their immediate term. About 16,000 stars have there been very precisely observed by MM. Müller and Kempf, with a polarising photometer employed on Zöllner's plan of comparison with an "artificial star." The results thus by various observers variously obtained are in general satisfactorily accordant; although the insecurity attending processes of correction makes some degree of divergence inevitable. A Photometric Catalogue gives the brightness of stars in all parts of the sky "reduced to the zenith." But the reduction is not by a simple or certain procedure. A law of light-absorption in the terrestrial atmosphere has first to be arrived at experimentally, and the experiments are difficult and delicate. Even at the zenith a heavy duty has to be paid, estimated by the Potsdam observers at 16 or 17, by Professor Pickering at 20 per cent; and the rate of increase towards the horizon differs at different altitudes, and probably in different climates as well. Hence the adoption of a uniform plan of reduction for photometric observations seems to be precluded; yet its absence must involve more or less serious discrepancies. They are, however, possible only when the range of conditions is wide; where they are fairly constant, extreme accuracy is attainable.

[1] *Harvard Annals*, vol. xiv. pt. i. (1884). For a comparison with the Oxford results see *ibid.* vol. xiii. p. 15.

[2] *Harvard Annals*, vol. xxxiv.

[3] *Ibid.* vol. l.

[4] *Ibid.* vol. xlv. 1901.

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In the Revised Harvard Photometry two stars, Aldebaran and *α* Crucis, are rated as almost exactly of standard first magnitude brightness, each being 2·6 times more luminous than the pole-star. They have in the northern hemisphere six superiors—Arcturus, Capella, Vega, Procyon, Altair, and Betelgeux, the standing of which has accordingly to be expressed by fractional numbers. Capella and Arcturus are of magnitude 0·2, signifying that each is eight-tenths of a magnitude brighter than Aldebaran, while the figure 0·06 attached to *α* Centauri conveys the fact of its superiority to *α* Crucis by just one magnitude. Carrying out the same system of notation, we get negative numbers for the designation of still higher grades of lustre. Sirius, for instance, sends us eleven times more light than Aldebaran; it excels the standard by two magnitudes and six-tenths, a pre-eminence compactly expressed by calling its magnitude −1·6. To find a star outshining Sirius we must go to our own sun, to which a rank can be assigned on the same scale. Its light, as measured by Alvan Clark in 1863, exceeds that of the dog-star 3600 million times. Bond made the disproportion 5970, Steinheil 3840 millions to one. From a mean of these insecure determinations, Professor Pickering fixed the sun's stellar magnitude at −25·4;[1] but various lines of inquiry, separately traced by Mr. Gore[2] and Sir David Gill, converge upon a much higher value lying between −26·5 and −26·8. It seems fairly certain, accordingly, that the splendour of Sirius is some 10,000 million times fainter than the blaze of sunshine in which we live.

The invention of the telescope itself does not mark an epoch more distinctly than the admission of the camera into the celestial armoury. All the conditions of sidereal research, in especial, have already been transformed by its co-operation. The versatility of its powers is extraordinary; no task has yet found it unready or incapable. It is the very Ariel of the astronomical Prospero.

This untiring serviceableness was made possible by the substitution in 1871 of gelatine for collodion as the vehicle for the salts of silver, the decomposition of which under the

[1] *Proceedings American Academy*, vol. xvi. p. 2.
[2] *Monthly Notices*, vol. lxiii. p. 164.

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influence of light forms the essential part of the photographic process. The new plates were, however, first used for "astrographical" purposes by Sir William Huggins in 1876. Since they are five times more sensitive dry than wet, exposures with them can be indefinitely prolonged. They may, besides, be prepared any desirable time before, and developed any desirable time after exposure, thus accommodating themselves in a really wonderful way to the needs of astronomers.

The unique power of the photographic plate as an engine of discovery is derived from its unlimited faculty for amassing faint impressions of light. By *looking long enough* it can see anything there is to be seen. Sir William Abney's experiments convinced him that no rays are too feeble to overthrow the delicate molecular balance of silver bromide if only their separately evanescent effects get sufficiently piled up through repetition.[1] By this capability of taking time for its ally, the camera leaves the eye far behind. With any given telescope much more can be photographed than can be seen, and the threshold has been crossed of a region of research, visually inaccessible, but open to exploration by the far-reaching chemical method.

The penetration of space has, nevertheless, limits. A *ne plus ultra* is imposed, if not otherwise, by the restricted possibilities of continuous exposure to the sky. Darkness does not last indefinitely, nor is it absolute while it prevails. There is always enough light scattered abroad to "fog" sensitive plates left long under its influence; and when fogging begins, portrayal compulsorily terminates. Thus, the plan first adopted by Dr. Roberts of obtaining a single picture by means of exposures renewed night after night can be availed of only with restrictions.

The telescope forming the image which imprints itself upon the prepared plate is always equatorially mounted, and has a motion given to it exactly concurrent with the revolution of the sphere. Yet the utmost mechanical ingenuity cannot make the concurrence absolutely perfect. Minute inequalities survive and need intelligent correction. Even more sensible are disturbances caused by the changes of atmospheric refraction with the ascent towards or decline from the meridian

[1] *Observatory*, vol. xii. p. 165.

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of the objects in course of delineation. For these reasons a photographic telescope has, as a rule, a guiding telescope attached to its axis, through which an observer watches to counteract, almost to anticipate, nascent tendencies to displacement. The strain upon the attention is severe; its endurance, upon occasions, for three, even four hours at a stretch, is no small proof of resolution.

Exposures can, however, be curtailed by shortening the focus of the photographic telescope, the image being thus rendered smaller, and—through the closer concentration of the same amount of light—more intense. For simply exploring the skies, sounding their depths, and dredging-up their contents, nothing can be better than the form of an ordinary portrait lens. With such a one, only two inches in diameter, the picture of the comet of 1882 was taken at the Royal Observatory, Cape of Good Hope, the "thick-inlaid" background of which afforded the first palpable revelation of the star-charting powers of the camera; and much of Professor Pickering's admirable work in sidereal photography has been done with a Voigtländer's "doublet" (two achromatic lenses in combination) of eight inches aperture and about forty-five focus. Objects imperceptible through the Harvard fifteen-inch refractor can be photographed with this instrument; and it has proved extraordinarily efficient for the rapid charting of stars and their spectra. The "Draper Catalogue" was indeed compiled wholly from materials collected by its means. In the "Bruce telescope," completed by Alvan Clark under Professor Pickering's direction in 1893, and mounted at Arequipa in 1896, after transmission through the Straits of Magellan, the same plan of construction was carried out on a larger scale. The object-glass has a diameter of twenty-four inches, the focal length is eleven feet. Stars down to the seventeenth magnitude are probably recorded on plates exposed to the strong concentration of light thus effected. The portrait-form of lens has the additional merit of giving a large field of view. Each photograph taken with the Bruce telescope covers, with very slight distortion, five degrees square (25 square degrees) on a scale of one minute of arc to a millimetre. The whole heavens could be charted on about two thousand such plates.

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Where accurate measurements are aimed at, however, the type of instrument represented by the MM. Henry's photographic telescope is preferable. The object-glass in this is of the ordinary achromatic kind, but corrected with reference to chemical, instead of to visual action. The rays selected to be brought to a focus are those to which, not the human, but the "photographic retina" is sensitive. The aperture is 13 inches, the focal length eleven feet; a plate-holder is substituted for an eye-piece, while a guiding-telescope of slightly inferior dimensions is enclosed within the same rectangular tube. The field of view with the Paris photographic telescope, within which definition may be considered as virtually perfect, is a circle three degrees in diameter,[1] covering an area of not quite five square degrees. Fully ten thousand of these plates (allowing for overlaps) will be needed to picture the sphere; and they are being taken in duplicate for the purposes of the International Celestial Survey. Eighteen instruments, modelled on that of the MM. Henry, are employed upon it; and the high quality of the data they will provide is assured. Yet thought quails before the quantity of materials presently to be dealt with. Eventually, we may fairly hope, they will be brought within the unifying grasp of statistical research; but only at a heavy cost of wearisome toil.

"Studies of the distribution of the stars," Professor Pickering remarked, "can now scarcely be undertaken in any way except by photography." But photography, to be really instructive on this point, must be combined with photometry. The portrayal of millions of stars projected side by side on a spherical surface tells us little or nothing of their relations to the immensity of space. This can only be found out, for the vast majority of them, by collecting statistics of the amount of light they send us. Hence the importance of the photometry of small stars. Yet no visual means have hitherto proved competent to deal with it. Eye-estimates, however guided and succoured by instruments, break down when pushed too far down the scale. The problem is evidently one of those reserved for successful treatment with the camera.

What is called "photographic irradiation" affords one means of attack upon it. This arises from the diffusion of

[1] *Bulletin Astronomique*, t. vi. p. 303.

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light within the substance of the gelatine film. The particles directly meeting the stellar rays reflect them irregularly all round to other particles, thus widening the area of chemical decomposition, and creating circular images which, with the same exposure and on the same plate, are found to vary in size with the magnitude of the stars they represent.[1] Thus, from a few stars of ascertained brightness, that of the rest imprinted with them may, down to a pretty low grade, readily be inferred. The faintest stars, however, give rise to dots so small that differential measures of them are scarcely practicable. The method is further compromised by the uncertainty of the law connecting the size of chemical star-discs with brightness. It is indeed a mere empirical formula varying with the conditions of observation. It is not the same for rapid as for slow plates; it is not the same for twinkling as for steady images.[2] There is no help but to treat each plate as a document apart, and to assign its constants independently; and this is to adopt an expedient, not to employ a system.

Nor does the scale of photographic effectiveness agree at all closely with that of visual sensibility. Colour has in this respect a strongly disturbing influence. The quick vibrations at the blue end of the spectrum are those most active in releasing silver from chemical bonds. Blue stars are consequently far more, and red stars far less conspicuous self-printed than to the eye. Photographs of chromatic double stars thus show curious reversals, a small blue companion often coming out superior to its yellow or reddish primary.[3] And tinted stars too faint for colour-discrimination with the telescope can sometimes be picked out on a negative, simply through anomalies of relative magnitude. Now differences of this sort occur not only in isolated cases but methodically. Their frequency, as Professor Kapteyn discovered in measuring the Cape Durchmusterung plates, depends upon celestial situation. It varies with galactic latitude. And the inevitable inference was drawn that "the stars of the Milky Way are in general bluer than the stars in other regions of

[1] *Astr. Nach.* No. 2884.
[2] Gill, Introduction to *Cape Photographic Durchmusterung*, p. 24.
[3] Espin, *Observatory*, vol. vii. p. 247.

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the sky."[1] Thus, photographic photometry has a very important bearing upon studies of sidereal construction. But a settled basis of principle is needed to give its results the full authority that should belong to them. At present, actinic magnitudes are derived very much at the discretion of individual observers. Perhaps the best way of treating them would be to take them for what they are worth, abandoning attempts to reduce them to scales of visual magnitude. They are worth a great deal.[2] In some respects, perhaps even more than magnitudes estimated by the eye. For their enumeration and classification may supply both geometrical and physical data regarding the stars; indications, that is to say, as to their arrangement in space, and indications besides of their assortment by affinity of constitution into indefinitely vast aggregations.

The photometry of nebulæ has, so far, obtained less than its due meed of attention. Sir William Huggins ascertained, in 1866, the extreme intrinsic faintness of such objects,[3] and there the matter rested until the universal agency of the camera was made available. Then, in 1884, Mr. W. H. Pickering described a mode of constructing a scale of photographic intensity by exposing a number of small squares at one side of a sensitive plate to a known light-source during different intervals of time.[4] These, developed with a nebula-picture subsequently imprinted, afford so many terms of comparison for the relative brightness of its parts. He drew in this way a set of "isophotal contours" in the Orion nebula, and the map representing them constitutes a record of present interest, and of possible future importance. The absolute brightness of the formation, in the central "Huygenian" region, was found to range between 70 and 140 units, the adopted unit being one-millionth of the light given by a standard pentane lamp. No further equally systematic attempts have been made to determine the luminosity of nebulæ; although its variability, assured in some cases,

[1] Introduction to *Cape Photographic Durchmusterung*, p. 22.

[2] Gill, *ibid.* p. xii. *note.*

[3] *Phil. Trans.* vol. clvi. p. 392. Cf. J. E. Gore, *Observatory*, May 1905.

[4] *Proc. Amer. Acad.* vol. xx. p. 512; *Harvard Annals*, vol. xxxii. p. 16. Sir W. Abney independently two years later invented a similar device, *Nature*, vol. xl. p. 472.

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suspected in many more, strongly suggests the desirability of establishing a fixed plan of measurement.

There is scarcely one of the numerous tasks of nebular astronomy that cannot be better performed photographically than visually. In the simple perception of faintly illuminated surfaces, the quickly fatigued living retina is left far behind by the imperturbable gaze of a sensitised plate; in their delineation, the subtlest human hand is at a similar disadvantage. Professor Holden gave his testimony to the effect that "every important result reached by his four years' study of the Orion nebula with the 26-inch Washington equatoreal," and very many not comprised in it, were attained by Dr. Common's subsequently taken photograph, which required an exposure of only forty minutes.[1] Spectroscopic inquiries, both stellar and nebular, are enormously facilitated by the substitution of permanent autographic records for sets of quivering lines, caught in their mean positions only by a keen glance at critical moments, and constantly liable to effacement by atmospheric waves. It is true that the range of observation is not the same in both cases. The plates in ordinary use ignore the lower end of the spectrum, but are affected by the higher vibrations which, by their quickness and shortness, evade the eye. "Orthochromatic" plates, sensitive to yellow and red rays, can, however, be produced by staining with eosin and other coal-tar dyes; but their use is attended by some inconvenience. Uniformity of light-action can scarcely be secured with them; they respond to it with a certain caprice; and are hence apt to yield spectra of a somewhat patchy brightness.

The wonderful comprehensiveness and adaptability of this method are strikingly apparent in the results obtained since 1886 at Harvard College. By no other means could the spectroscopic stellar survey executed there and at Arequipa, its southern dependency, have been carried out on so great a scale. The results constitute a veritable spectroscopic Durchmusterung, complete to about the ninth magnitude; and the work is now being extended to fainter stars. The manner in which it was conducted, although described by Fraunhofer and Secchi, was virtually novel. A prism large enough to cover

[1] *Overland Monthly*, November 1886.

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the entire object-glass is placed in front of it. The stellar beams are thus analysed before they are concentrated; every stellar image is transformed into a prismatic riband; and stars by the dozen or by the score print their separate spectra on a single plate with a single exposure. Slit and cylindrical lens are alike rejected; the diurnal motion is employed to widen the spectral bands sufficiently to bring out their distinctive features. That is to say, the stars are allowed to "trail" slightly across the direction in which their light is dispersed. The results are admirable; innumerable lines are clearly recorded; but the highest degree of accuracy cannot, in the absence of any system of reference-lines, be given to determinations of their positions. Mrs. Fleming's scrutiny, meantime, of the records thus profusely accumulated, has led to the discovery of hundreds of objects remarkable for the unusual quality of their light; and the spectra of about 1800 bright stars, photographed on a larger scale with more powerful instruments in the northern and southern hemispheres, have been discussed and catalogued respectively by Miss Maury and Miss Cannon.

For detailed identifications, the more laborious plan adopted by Sir William Huggins in 1879 is still pursued. The stars are taken one by one; their rays are admitted through the postern-gate of a slit, and record their peculiarities side by side with a comparison-spectrum providing starting-points for measurement. The "Atlas of Stellar Spectra," published by Sir William and Lady Huggins in 1899, exemplifies the perfection with which details, otherwise inaccessible, can thus be brought into view. Glass, which is strongly absorptive of the shorter wave-lengths, is excluded from their apparatus. The stellar rays admitted to it are concentrated by an 18-inch speculum, and dispersed by quartz prisms. Introduced by Sir William Huggins in 1868, the spectroscopic method of determining stellar motions in the line of sight was perfected, ten years later, by the change of venue effected on the initiative of Dr. Vogel, from the eye to the plate. Its superiority has, in this difficult branch, triumphantly asserted itself. The precision photographically attainable in measuring spectral shifts is chiefly due to the virtual elimination of the effects of air-troubles. The lines

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from which information as to movement has to be gathered depict themselves in their normal places. Their waverings, so baffling visually, are chemically ineffective.

Nor is it only here that the autographic mode of procedure attains a refinement on a par with its power. The subtlest problem of stellar astronomy is that of annual parallax. It leaves room for no compromise in the matter of accuracy, yet it has been solved with the aid of the camera. Professor Pritchard's careful and persevering experiments established the validity of photographic determinations of parallax, and so furnished to the sidereal armoury a new weapon of precision and long range. It happens, moreover, that the objects most inviting to the one mode of treatment are precisely those reached with difficulty by the other. Stars too faint for the eye to deal with satisfactorily come out on negatives in neatly measurable form; while the brighter stars suitable for observation with the telescope and micrometer give distended photographic images unpromising for exactitude.

There are indications that reflecting telescopes will before long regain the position of preference which Fraunhofer's skill in grinding lenses forced them to abdicate. They have over their rivals the special advantage of being perfectly achromatic; they collect at one focus *all* the rays, visible and invisible, striking them. This the very best refractors fail to effect. However skilful the combination of different kinds of glass, a large amount of light is necessarily "thrown away."[1] Opticians have to choose what sections of the spectrum they will turn to account, and neglect the rest. Photographic refractors are for this reason useless in ordinary observation. The images they give are wholly built up out of blue light, while the light proper for seeing by wanders unserviceably astray. The plates exposed with them must accordingly be sensitised in correspondence with the mode of their correction. No tolerable results could be got with orthochromatic plates in the Henry telescope.

These drawbacks are, nevertheless, to a great extent outweighed by countervailing prerogatives. Refractors are more manageable than reflectors. They are less sensitive to slight

[1] Sir H. Grubb, *Monthly Notices*, vol. xlvii. p. 309.

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strains, less intolerant of unequal pressures; they accommodate themselves better to mechanical exigencies, can be more rigidly mounted, hence made to follow more strictly the circling of the sphere, and so to keep a steadier hold of the objects in the field of view. Where measures of precision are chiefly aimed at, choice is thus naturally directed to them, and they have been stamped as the official instruments of celestial photography by their adoption for the vast star-charting operations decided upon at the Paris Congress of 1887. The splendid nebular pictures, on the other hand, obtained with reflectors by Common and Roberts, and more recently in America by Keeler and Ritchey, prove their superlative fitness for tasks of delineation. Moreover, their future extensive employment in spectrographic work seems inevitable. With refractors, the range of good spectral definition is narrowed by their inequalities of focal concentration, while reflectors display in uniform distinctness the whole light-gamut from end to end. This point of superiority is very important, since a partial view of stellar spectra is, in many cases, not only unsatisfactory but misleading. All telescopic varieties, in fact, find their place in the boundless fields of photographic research. Mirrors do not exclude lenses; instruments of short focus have a special function, while for other purposes those of long focus are preferable. The needs of sidereal investigation are manifold; they claim subventions from every quarter; they invoke the most diversified forms of assistance. And their demands have been met by a generous largesse of inventions and contrivances.

The foundation of stellar astronomy is, as we have said, in infinitesimal accuracy. It could not otherwise exist, since the quantities concerned are so small as to disappear amid the errors of rough observations. But for its progress, something more is required. A few scattered items of knowledge do not constitute a science. The word implies the suffusion of a subject with intellectual light derived from large inferences. Large inferences, however, must be based on a plentiful store of facts; and the facts collected by sidereal study are, even yet, few compared with its innumerable objects. They are, indeed, being continually multiplied. The alliance with photography

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has widened the basis of reasoning without impairing its security. By no other means could the desired information be supplied, not only in abundance, but with the needful promptitude. For, to a certain extent, the work has to be done against time. Just as rapid intuitions are necessary for following a long train of mathematical reasoning, because, where the steps are laboured, the wearied faculties at last refuse to continue to take them, so some degree of forward impetus is indispensable for sustaining the universal interest which gives a subject its vitality, but declines to follow too tardy an exchange of one halting-place for another.

Thus, not merely what it can do, but the rate at which it can do it, has to be considered in estimating the value of photography as an aid to astronomy. And there is little fear of its admitting lassitude through sluggishness of pace. It keeps up a very "Sturm und Drang" of progress. The decuple powers of enumeration desired by Homer for cataloguing the crowd of Greek ships are far outdone by it. Its instrumentality, moreover, came to hand just when the multitudinous character of the problem set by the heavens began to be grasped in all its formidable reality.

The swiftness of the photographic method is due, not alone to the great number of objects it can register together, but to the dispersion and division of labour it makes possible. Records obtained by it have the enormous advantage of being permanent. They fix the flitting incidents of the heavens as the phonograph fixes the transient accents of the human voice. All the scanty hours of unclouded darkness can thus be devoted to securing materials for subsequent investigation in daylight or bad weather. Innumerable experts may be employed in this way at remote places and with different ends in view. A single negative may be communicative regarding stellar photometry, distribution, parallax, proper motion; its comparison with others serves to test variability, or even to fix the epoch of some mysterious sidereal cataclysm. Yet the possession of pictures of celestial objects does not in itself constitute an increase of knowledge. They contain *latent* information, just as the skies themselves do, but the educing process by which it is made *sensible* is as necessary in the one case as in the other. Zeal in securing them is accordingly of

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slight avail without industry in discussing them, whether personally or by deputy; for astrographical tasks are easily capable of delegation. Star-prints are indeed usually dealt with by specialists in measurement, whose skill has been rewarded by many noteworthy discoveries. Those, too, that the future has in reserve will doubtless fall much more freely to the share of investigators armed with microscopes for the bisection of star-dots on glass plates than of telescopic watchers of the heavens.

Not that the telescope is, or ever can be superseded. On the contrary, the enlargement of its capacity becomes more desirable with every fresh addition to the apparatus used in conjunction with it. Modern sidereal astronomy may be said to *live on light.* Large telescopic apertures are a *sine qud non* for its growth and activity. A considerable proportion of the objects it has to do with are, in fact, beyond the range of small instruments. It is, however, as important to economise as to collect the far-travelled rays from the stars; and in this direction little has been accomplished. Under the best conditions, no more than 5 per cent of the light striking the 40-inch object-glass of the Yerkes refractor actually reaches the sensitive film after transmission through the great Bruce spectrograph; and although the waste in other forms of apparatus is less formidable in amount, they cannot yield results of equal precision. For obtaining legible records of the faintest spectra, none can compete with the slitless spectrograph employed in connection with the Crossley reflector at the Lick Observatory. How much of the incident light it turns to account has not been ascertained; but stars of the fifteenth magnitude have none to spare, and their rays can be successfully analysed on Mount Hamilton.

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CHAPTER III

THE STARS AS SUNS

THE stars, speaking broadly, are suns. But what is a sun? We can only reply by taking function into consideration. A sun is a great radiating machine, and the obvious criterion for admission to the order is fitness for this office. Qualification to be a centre of light and heat is the dominant characteristic of each of its true members. Now the solar emissive activity is concentrated in a shining shell of clouds known as the "photosphere," which the entire energies of the *organism* (so to speak) seem directed to maintain and renew. And with reason, since its efficiency as a radiator depends upon the perpetuation of the condensing process by which this brilliant surface is produced.

The possession of a photosphere must then be regarded as an essential feature of the suns of space. But such a structure can only be formed in an incandescent atmosphere, the action of which modifies, more or less powerfully, the light traversing it. The spectroscope can, in fact, alone decide whether a given sidereal object be, in the proper sense, a sun. For it is not so much the quantity as the quality of its radiations that determines the point. They must be such as can be supposed to emanate from condensed and vividly glowing matter bathed in cooler, though still ignited vapours. That is to say, they must, when dispersed by refraction or diffraction, constitute a fundamentally unbroken prismatic band, marked *incidentally* by effects of absorption. A continuous range of vivid light, crossed by dusky lines, is hence the distinctive spectrum of a sun.

The enormous light-power, and, so far, the solar nature of

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the stars, followed as a corollary from the Copernican theory, since at the unimaginable distances implied by their apparent immobility while the earth performed its vast circuit, they should otherwise have been totally invisible. But the analogy could be strictly tested only by spectrum analysis, and it proved virtually complete. Complete, that is, for the great majority of the stellar populace. There is a residuum in which it is impaired; there are a few scattered instances in which it is actually overthrown.

This degradation of type shows itself in different ways. Absorption in some cases becomes so immoderate as well-nigh to smother the original light of the star; the atmosphere in others outshines the photosphere, giving rise to bright instead of dark lines in the spectrum; while in certain objects a similar effect appears to be produced rather by a paucity of photospheric, than by the intensity of atmospheric radiation. When the failure has gone so far that the light of a seeming star, analysed with the spectroscope, is found to consist chiefly of isolated rays of various colours, then the object approximates more to a nebula than to a star. It certainly cannot lay claim to the designation of a sun.

But as in the other kingdoms of nature, so here; there are no abrupt transitions. Continuity is everywhere maintained. The descent from a perfect sun to an undoubted nebula is effected without interruption. Hence, inevitably, some uncertainty in classification. Broad divisions are easily established, but hard and fast outlines to those divisions cannot be drawn. "Frontier-instances" abound, and compel recourse to somewhat arbitrary distinctions. We propose, in the present chapter, to consider only bodies of assured status, with radiative machinery in full working order — bodies, as to the essentially sun-like nature of which there can be no difference of opinion.

The four spectral types discriminated by Father Secchi still form the basis of arrangement. They may conveniently be designated as Sirian and solar, Antarian and carbon stars, all showing continuous spectra crossed by dark lines of absorption, to which, in the two last varieties, dusky bands and flutings are superadded. The Sirian order, however, as originally described, included certain bright stars with seem-

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ingly blank spectra, prominent chiefly in the constellation Orion; and these have gained such importance through the discovery of terrestrial helium as to compel their relegation to a class apart. Thus, Secchi's white stars have, as it were, spontaneously ranked themselves into two great battalions, and we shall consider first those that came last to full recognition.

Stars of the "Orion" quality are purely white; their light approximates to being in the native state; that is to say, it is scarcely modified by the arresting action of their atmospheres. Yet it is not wholly characterless. Hydrogen and helium, especially, have left their stamp upon it. Fig. 1 of Plate II. reproduces, by the kind permission of Professor Pickering, a spectrograph of ϵ Orionis, the middle star in the Belt, taken at Arequipa, November 10, 1896, with the 13-inch Boyden refractor. The dispersion was produced by means of a train of prisms in front of the object-glass; no slit was used, consequently no comparison could be made available; and the exposure allowed was of 106 minutes. The darkening at either end is due to the limited range in sensitiveness of the plate employed. Helium-lines are nearly as strong as those of hydrogen in the spectrum of ϵ Orionis; and their association by Sir Norman Lockyer and others with the newly unearthed gas encouraged Dr. Vogel, late in 1895,[1] to search for further signs of their presence in a large collection of stellar spectrograms, prepared at Potsdam by Dr. Wilsing. To his surprise, he found Orion-stars to be fairly numerous all over the sky; and the late Mr. McClean's researches proved them to be still more prevalent in the southern than in the northern hemisphere.

They are, for several reasons, of particular interest. Sidereal genealogists assign to them a very early standing. They seem, indeed, to occupy a position intermediate between true nebulæ and Sirian stars. This conclusion is enforced, first, by the visibility of nebulous appendages attached to many helium-stars; next, by the low density which is one of their least doubtful characteristics. And it obviously implies that they have made less progress in contraction through cooling than globes of more substantial build. But even

[1] *Sitzungsberichte*, Berlin, October 24, 1895.

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Photographed Stellar Spectra (Pickering).

Fig. 1. ϵ Orionis. Fig. 2. Sirius. Fig. 3. Canopus. Fig. 4. Capella.

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among helium-stars themselves gradations of age are perceptible. Miss Maury arranged them into six groups,[1] corresponding, it was plausibly supposed, to so many stages of advance in condensation. One of the earliest of her stars, θ Orionis, is significantly placed at the core of the great Fish-mouth nebula; and in the species to which it belongs, metallic absorption is barely discernible, while some peculiar lines, identified with hydrogen by Pickering and Rydberg, come into view, together with a few delicate triplets shown by McClean to originate from oxygen. Helium and hydrogen are besides represented by their usual sets of rays. Although some advance from the immature state of θ is marked by the spectrum of ϵ Orionis, it still bears the impress of oxygen and "cosmic" hydrogen. Silicon-absorption is unmistakable in Bellatrix; β Crucis, one of the gems of the Southern Cross, is an exemplary oxygen-star; and, at the stage reached by Algol and Rigel, primitive symptoms have been superseded by the clear emergence of magnesium and calcium-absorption.

To resume. Helium-stars have these special features. They possess envelopes of helium capable of selective action upon light. Some among them, and notably those with nebular affinities, show dark rays of oxygen and cosmic hydrogen. In all, metallic absorption is feeble. The photospheric radiance of all spreads abroad into space sensibly unmodified by atmospheric stoppage. Finally, they tend to congregate in the Milky Way, particularly in the southern hemisphere.

Sirian stars resemble their predecessors in their brilliant whiteness and comparative freedom from atmospheric encroachments. There is little or no trace in them of the general veiling effect by which our own sun is shorn of a large proportion of his more refrangible beams. The Sirian spectra, although not intact, are entire, and are hence especially strong in their ultra-violet sections. To this immunity from absorptive attacks there is one remarkable exception. The sign-manual of hydrogen is stamped upon them with extraordinary intensity. A number of metals are also present, but they show lines too faint and fine for easy recognition. Fraunhofer's "D," the ubiquitous double-line of sodium, is nevertheless obvious, as well as the "K" of calcium and the "blue"

[1] *Harvard Annals*, vol. xxviii. p. 15.

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line of magnesium. With the best definition, too, multitudinous fine striations, a large proportion of them due to iron, can be photographed. Thus, in the spectrum of Sirius (see Plate II. Fig. 2), Mr. S. A. Mitchell counted on his plates 75 lines in the restricted section comprised between two consecutive hydrogen-lines (Hβ and Hγ).[1]

Photography has indeed played an essential part in the investigation of Sirian spectra. The strength of their ultra-violet radiations lends to the method peculiar efficacy in dealing with them; and the advantage was turned to the fullest account by Sir William Huggins in 1879.[2] The impressions secured by him with an apparatus from which glass was wholly excluded, afforded a discovery memorable, not in the history of astronomy alone, but in that of molecular physics as well.

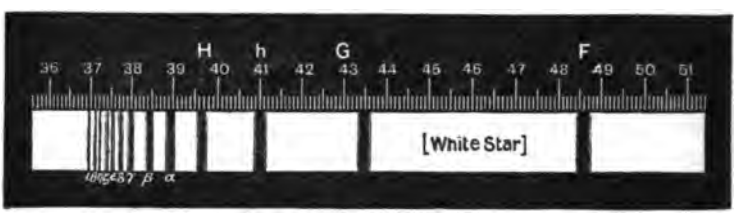

Fig. 1.—Spectrum of Hydrogen in White Stars (Huggins).

A photograph of the spectrum of Vega obtained with one hour's exposure contained twelve strong lines (shown in Fig. 1) forming a group in obvious rhythmical connection. They crowd together more and more as their wave-lengths shorten. A common origin for the entire at once suggests itself: and, on the ground that its two most refrangible members were already known as hydrogen-lines, Sir William Huggins did not hesitate to pronounce hydrogen responsible for all. His inference has been amply justified. Seven of them proved to have been, a short time previously, photographed directly from glowing hydrogen, by Professor H. W. Vogel;[3] and the complete set was similarly procured later by M. Cornu,[4] but with

[1] *Astroph. Journ.* vol. x. p. 32.
[2] *Phil. Trans.* vol. clxxi. p. 669.
[3] *Astr. Nach.* No. 2301.
[4] *Journal de Physique*, t. v. p. 341 (1886).

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extreme difficulty. Although the purified gas filling the capillary tube placed in front of the slit was excited by powerful electrical discharges, its highest radiations took no less than three hours and a half to get satisfactorily printed. Some idea may thus be gained of the intense incandescence reigning in the remote stellar atmospheres from which they were first derived.

The law regulating the sequence of hydrogen-lines was assigned by Balmer in 1885.[1] It is a purely empirical formula that may be modified at will; yet since it has availed, not only to connect together numerically lines already observed, but also to locate additional ones, it must correspond to something essential in nature. The members of the "Huggins-series" are really indefinitely numerous. They crowd up towards a limit in the ultra-violet, which, like the asymptote of a curve, is continuously approached, yet never actually attained. Subjoined are the wave-lengths, in ten-millionths of a millimetre, of the first twenty, as given by Dr. Kayser.[2] Their designation by the letters of the Greek alphabet is now all but universal.

Designation.	Wave-length.	Designation.	Wave-length.
H α	6563·07 (Fraunhofer's C)	H λ	3734·51
H β	4861·52 („ F)	H μ	3722·08
H γ	4340·63 (near „ G)	H ν	3712·11
H δ	4101·90 („ *h*)	H ξ	3704·00
H ϵ	3970·22 („ H)	H o	3697·29
H ζ	3889·20	H π	3691·70
H η	3835·53	H ρ	3686·97
H θ	3798·04	H σ	3682·95
H ι	3770·77	H τ	3679·49
H κ	3750·30	H υ	3676·40

Theoretical limit λ 3646·13.

This series was believed to be solitary until Professor Pickering announced, in 1897,[3] his identification of a companion-set of lines in the peculiarly constituted southern star, ζ Puppis. Much knowledge had by that time been gained regarding spectral series. The pattern set by hydrogen had been found to be conformed to, with variations, by the

[1] Wiedemann's *Annalen*, Bd. xxv. p. 80.
[2] *Handbuch der Spectroscopie*, Bd. ii. p. 506.
[3] *Astroph. Journal*, vol. v. p. 92.

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emissions of a number of other substances; and what might be called a typical arrangement of three series linked together by a slightly modified common formula, had come to be recognised as prevalent. This triple set consists of two "subordinate" series, converging towards the same limiting wave-number,[1] and a "principal" series, composed of much more widely separated lines. Now Pickering's series is constructed accordantly with Huggins's series; it runs up to an identical "head" in the ultra-violet; and was hence at once, and beyond the possibility of mistake, associated with hydrogen. Yet it cannot be procured artificially. We are entirely ignorant of the conditions under which it is displayed. It is only certain that they prevail in early helium stars, and have become abolished by the time the Sirian stage is reached.

The fact is a memorable one that the true character and full extent of the hydrogen-spectrum became known through astro-physical inquiries. It shows with what curious unexpectedness the obligations of one science to another may be repaid, and exemplifies the advantages to be reaped by terrestrial chemistry from extending its experimental range to the heavenly bodies. The "white star" set of rays has furnished a clue to many a spectral labyrinth, and its underlying principle of order has been proved, by extended laboratory-research, to be of vital importance in molecular physics. The modulated behaviour of different rhythmical series under varied treatment is profoundly significant, and indicates one of the most promising methods for probing the secrets of material structure and ethereal relationships.

Disproportion in strength between hydrogen and metallic lines reaches a maximum in the spectrum of Sirius, a section of which, from a superb Harvard photograph, is shown in Plate II., Fig. 2. Helium makes no effect in it; and the change of type from ϵ Orionis could be discerned—even if every other symptom of it were absent—from the substitution for the "blue" helium-line (at λ 4472) of a dark magnesium-ray slightly less refrangible. This trait of magnesium-absorption is relatively much stronger in Sirian stars than in the sun and his analogues; and a particular meaning is lent to the dis-

[1] Wave-numbers, or frequencies of vibration, are the reciprocals of wave-lengths, and are always substituted for them in numerical calculations.

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crepancy by the circumstance that the line in question is (in Sir Norman Lockyer's phrase) "enhanced" in passing from the electric arc to the spark. Silicon is the only non-metallic element besides hydrogen identified in Sirius; and here again, the identification is by means of lines intensified in the electric spark.

An exposure of eighty-two minutes, with the 13-inch Boyden refractor, was given at Arequipa to the negative from which Plate II., Fig. 3, is copied. The spectrum represented is that of the magnificent Canopus (*a* Carinæ). The diminished width of the hydrogen-lines, and the augmented conspicuousness of the calcium K, signify a decline from the condition of Sirius towards that of our sun. Many distinctively solar lines have asserted themselves; yet no less than twenty members of the hydrogen-series may still be seen or photographed, while only four can be clearly made out in the sun. There is reason to believe that the measure of their affluence gives a searching test of stellar constitution.

Although the hydrogen spectrum is dominant throughout the first order of stars, it is not in all represented with equal emphasis. The diffuse lines constituting it in Sirius and Vega show, in descending gradations of fineness, in Castor, Fomalhaut, and Altair. They appear, moreover, less solitary in proportion as they become less intense. Their all but exclusive possession of the ultra-violet field is progressively encroached upon by the development of other spectral lines. The co-ordination of the two kinds of change may be expressed by the general statement that *the prominence of rays due to absorption by metals in the spectra of white stars varies inversely with that of the hydrogen series.* When the hydrogen-rays become effaced from the invisible, and cease to dominate the visible part of the spectrum, the second, or solar type of stars is reached.

These are about one-sixth less numerous than the first kind. We may take as examples: Capella, *a* Ursæ Majoris, *a* Cassiopeiæ, *a* Arietis, *ε* Carinæ, *a* Serpentis, Aldebaran, and Arcturus. The pole-star, Procyon, *a* Leporis, and *a* Persei, stand nearly midway between the two groups.

A golden tinge like that of sunlight betokens, in stars of the second order, a spectrum more or less perfectly similar to

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that of the sun, delicately ruled from end to end through the absorptive effects of a great variety of metallic vapours; non-metallic substances are represented only by hydrogen, associated in the sun with silicon, oxygen (a trace), and carbon. The extent to which the lines are crowded together may be judged of from the photographed spectrum of Capella depicted in Plate II., Fig. 4. Dark hydrogen-rays are present, but with no pre-eminence, and No. 5 of the series (Hϵ) probably lurks concealed within the shadow of an obscure diffuse band which covers its place. This band was named by Fraunhofer H, and its companion, a little higher up, is designated K. The pair form the most strongly-marked feature of the spectrum of calcium when raised to the highest pitch of incandescence; the ordinary flame of the substance shows them but dimly.

They are peculiarly characteristic of the spectrum of solar prominences. Daylight observations at the edge of the sun disclose them as invariably brilliant in the chromosphere, and shining up to the very summit of each one of its flame-like extensions. Moreover, during the total eclipse of May 17, 1882, the violet radiance of H and K flooded the shadowed part of our atmosphere, and dimly illuminating the purple disc of the moon, was scattered far out among the "aigrettes" of the corona.

Corresponding symptoms of the phenomenal importance of calcium-vapour in the sun's economy had been already detected by Professor Young in the course of his daylight spectroscopic observations. But they were not fully appreciable until photography was made available for their continuous investigation. H and K lie at the verge of the visible spectrum; the eye perceives them with some difficulty; while the chemical retina is extremely sensitive to their vibrations. Further, the black bands due to their absorption have, in the Fraunhofer-spectrum, dark shadings symmetrically attached to them, by which the bright rays of the same refrangibility used in prominence-photography are effectively sheltered against atmospheric glare. This convenience was amply turned to account when Professor Hale and M. Deslandres independently adapted to the purposes of daylight solar photography Janssen's invention of a double slit for isolating individual qualities of light. In particular,

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it led them both to the discovery that the sun's disc is overspread with wreathed shapes of glowing calcium, designated by Professor Hale "flocculi," and regarded as expansions of vaporous masses, lying at the base of the chromosphere, and fed by mounting torrents from the sun's interior.[1] The intensity of their radiation appears anomalous, and may, he thinks, need to be explained otherwise than by mere elevation of temperature.

Presumably, all solar stars possess calcium-appendages equally well-developed with those of the sun. Their spectra are impressed with the same powerful H and K absorption; and it is hardly conceivable that a stamp so peculiar, and so emphatically impressed, should have a different meaning in them from that deciphered in the one star accessible to interpretative research. The calcium H falls, nevertheless, very near indeed to the hydrogen Hϵ (see Plate II., Fig. 3), the difference of their wave-lengths amounting to no more than one ten-millionth of a millimetre, and it is only on the best negatives that they can be separately distinguished. Usually, either the hydrogen-line is so widened as to mask the calcium-line, or the calcium-line as to enwrap the hydrogen-line. Professor Young, however, saw them side by side, *bright*, during his observations of prominences in 1879-1880; and they appeared *dark* in a photograph of the spectrum of α Cygni taken at Harvard College, November 26, 1886. In this star, a spectrogram of which, taken under Professor Pickering's direction in 1893, is reproduced in Plate III., Fig. 1, the hydrogen rays have thinned down almost to their solar condition, while other metallic lines are fine yet pronounced. Such a critical balance of conditions alone made possible the individualisation of the two lines on the earlier Harvard plate.

Thus, while the double origin of H opens the way to misunderstandings, the state of the calcium-line at K is a most useful index to the physical condition of a star.[2] Next to the mode of appearance of the hydrogen series, it is perhaps the feature most deserving of study in analysed starlight. The substance emitting both H and K is evidently of first-rate importance among the vapours surrounding the

[1] *Publications of the Yerkes Observatory*, vol. iii. part i. p. 16.

[2] As Sir William Huggins pointed out in 1879.

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sun. And that it is, in fact, the metal calcium in a highly rarefied state, was proved by the experiments of Sir William and Lady Huggins in 1897.[1] The hypothesis of its dissociation in the sun thus remains unverified. It is true that the twin-lines H and K differ in their relationships from most of the other component-rays of the calcium spectrum. They stand aloof from any arrangement into series; they exhibit special effects under pressure, and—we may add with approximate certainty—in a magnetic field. Such personalities of behaviour in spectral lines are familiar in the laboratory as well as in the heavenly bodies. They do not seem to indicate a compound nature (as ordinarily understood) in the emitting element; yet they undoubtedly suggest a less rigid uniformity of structure among its minute vibrating particles[2] than had, until recently, been held compatible with the accepted principles of physical chemistry.

Some slight diversity of detail is to be found among spectra of the second type. In the main, however, they are closely alike; and the chemistry of the sun may be called normal for all his congeners. The model solar star was long supposed to be Capella; and it is true that in the invisible, as well as the visible part of its prismatic light, all the characteristic solar groups exist in about their solar strength. Dr. Scheiner identified with extreme precision 255 lines photographed from Capella (between wave-lengths 4124 and 4638), with lines derived from the sun;[3] and it appeared reasonable to infer an almost perfect constitutional similarity between the two bodies. Capella has since, nevertheless, proved to be a double star with a compound spectrum; and the secondary component gives light resembling that of Procyon or Canopus more than that of the sun. Thus, the ultra-violet hydrogen-lines distinguishable in the joint spectrum belong to this star, and not to the primary body, which is genuinely solar. In the sun itself, the hydrogen-series has no more than four representatives. Professor Ames was able to ascertain, through the cloak of calcium-absorption, the absence of Hϵ, its fifth member;[4] and some vague shadings, noticed

[1] *Astroph. Journal*, vol. vi. p. 77.
[2] Kayser, *Handbuch der Spectroscopie*, Bd. i. p. 579.
[3] *Astr. Nach.* No. 2923.
[4] *Phil. Mag.* vol. xxx. p. 54, series v.

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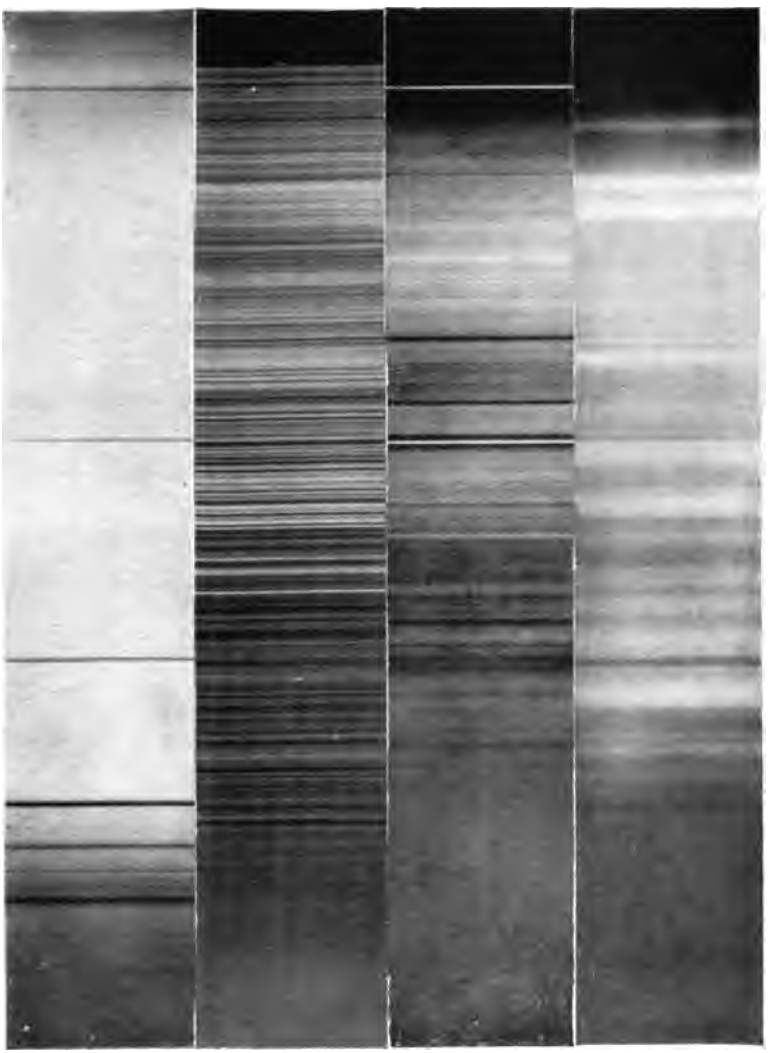

Types of Stellar Spectra (Pickering).

Fig. 1. α Cygni. Fig. 2. Betelgeux. Fig. 3. μ Centauri. Fig. 4. γ Velorum.

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by Rowland near the positions of some of its more refrangible associates, are of uncertain meaning. Solar stars of pure type should, then, display four, and only four, dark rays of hydrogen; the presence of additional ones gives rise to a suspicion of duplicity. The chief member of the southern star-pair, *a* Centauri, again offers a perfect example of a sun-like spectrum; and this star, being the sun's equal in mass, may be concluded to be similar to it also in temperature, density, and light-power. The uses, for purposes of comparison, of an authentic model-sun have been expressly adverted to by Sir David Gill.

In Aldebaran this standard is pretty widely departed from. The pale rose tint of its light is accounted for by the slightness of absorptive effects in the red end of its spectrum, while numerous lines modify the yellow and green, and the violet rays are so feeble that, with an exposure *fifty times* that required for Sirius, Sir William Huggins, its original spectrographer, obtained only an impression virtually conterminous with the perceptive range of the eye. This feebleness of chemical action is perhaps due, not to intrinsic deficiency of blue light, but to its stoppage in the vaporous envelope of the star.

The spectrum of Arcturus (*a* Bootis) varies from the solar pattern in the same direction, though not to the same extent, as that of Aldebaran. A section of its blue part is copied in Plate IV., Fig. 1, from a photograph taken by Professors Frost and Adams in 1903 with the great Bruce spectrograph of the Yerkes Observatory. Spark-lines of titanium furnished a comparison-spectrum; and the emphatic nature of the coincidences gives an idea of the strength of absorption by that metal in the star's atmosphere. In the sun also, titanium plays a remarkable part. The lines due to it, although mostly faint in the Fraunhofer spectrum, come out with augmented intensity in the spectra of agitated spots; and the copious photographic record of its emissions, especially as obtained by Mr. Evershed during the Indian eclipse of 1898, assign it a place among the permanent constituents of the solar chromosphere and prominences.[1] In the spots and eruptive appendages of Arcturus, we may be reasonably sure that it is still more plentiful and active.

[1] Maunder, *The Indian Eclipse*, p. 70.

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No line of demarcation can be drawn between helium and Sirian stars on the one hand, or between Sirian and solar stars on the other. And the presumption is strong that the transition from each class to the next is effected by actual development; that the same object passes successively through the indicated changes. The chief reason for hesitation in adopting this view is that the various stellar orders are not indifferently scattered over the heavens; but we understand very little of what such distinctions really imply. There is, besides, some direct evidence that helium stars are those most recently condensed from nebulæ. Some of them appear to be as yet not wholly detached from their cloudy matrices; while Sirian and solar stars, although they may be projected casually upon a nebulous background, are probably never, in point of actual fact, nebulous. Nor is the supposition admissible—as the case stands at present—that helium stars can progress to the solar condition otherwise than by the prescribed route. The intermediate Sirian type must apparently be conformed to before the third station on the long journey comes within reach. Some authorities, it is true, believe that it may be dispensed with, and that α Cygni is an example of stars traversing this evolutionary short-cut;[1] but the better opinion is adverse to such a possibility.

We may now briefly reconsider the course and kind of modification undergone by the stars, so far as we have yet taken them into account. In the first place, there is a steady increase of general absorption. The light of Bellatrix (γ Orionis), for instance, attains outer space substantially as it left the star's photosphere. Its native bluish tinge subsists; the proportionate intensities of its variously refrangible sections remain unaltered. But our sun's proper atmosphere, or "smoke-veil," arrests a large percentage of his violet radiations. The solar disc is, indeed, quite brownish near the edges, because near the edges the light cuts obliquely through the reddening strata, and suffers in consequence heavier encroachments. Could they be stripped off, the sun would blaze with at least once and a half times its present brightness, and would show a steely lustre very different from the golden radiance we are accustomed to. There is hence no

[1] Scheiner, *Potsdam Publicationen*, Bd. vii. Th. ii. p. 331.

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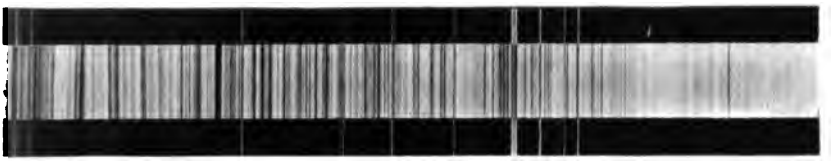
1.



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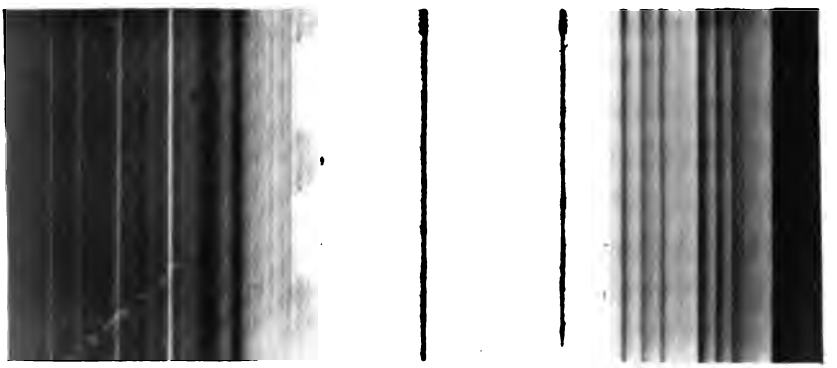

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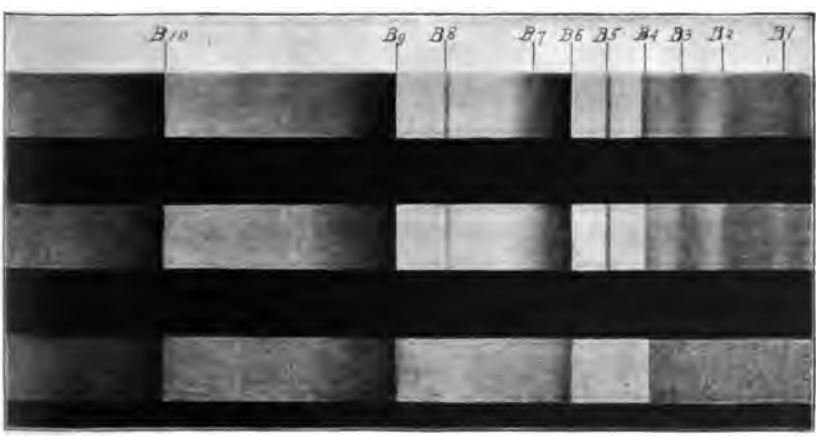

Stellar Spectra of three Types.

1. Spectrum of Arcturus with Titanium Comparison-Spectrum (Frost).
2. Spectrum of *o* Ceti (Pickering).
3. Spectra of the fourth type (Dunér).

(From Decennial Publications of the University of Chicago.)

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warrant for asserting that the emissive outpourings of solar orbs differ intrinsically from those of Sirian or of helium stars. It is certain only that they are strongly modified by selective absorption which has no appreciable effect upon spectra of the earlier types.

The signs of specific absorption, as helium grow into solar stars, alter by insensible gradations, but according to a visibly consistent method. From beginning to end of the series there is a steady increase in the number and intensity of metallic lines, very notably in those of iron, which, next to the giant-bands of calcium, constitute the dominating feature of the solar spectrum, yet are imperceptible in the prismatic light of Rigel and Bellatrix. Absorption by helium and oxygen[1] comes in at the start, but has a strictly limited time-range. It scarcely brooks competition, sharing the field only with hydrogen in its terrestrial and cosmic forms; metals, in the earliest stars, showing only by a faint streak of magnesium. As they begin more numerously to assert their presence, helium lines become effaced, and those of hydrogen attain their maximum development. But the Huggins-series is now alone represented, for the Pickering set is even shorter-lived than the helium rays, and it appears exclusively in what are supposed to be the earliest stars. This is an extraordinary circumstance, most baffling to comprehension. There is no other known instance of such independent behaviour on the part of a spectral series. Nor can its meaning, in the total absence of terrestrial experience, be interpreted by so much as a plausible conjecture. If the Pickering lines could be induced to show in vacuum-tubes some basis would be supplied for reasonings on the subject; but attempts to elicit them have, so far, proved altogether fruitless. It is also important to remember that, in the stellar succession, the character of metallic absorption changes as well as its strength. The few traits of it which appear compatible with the display of helium are—in Sir Norman Lockyer's phrase—"enhanced" lines; lines which vivify notably when for the illuminative agency of the electric arc a disruptive spark-discharge is

[1] Frost and Adams suspect that oxygen-stars may be traversing a road parallel to the main track of evolution. *Publ. University of Chicago*, vol. viii. p. 107.

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substituted. In a general sense it may indeed be said that the spectra of the sun and of solar stars imply a state of things in their reversing layers analogous to that prevailing in the arc-light, while in helium and Sirian stars the conditions of the spark are more nearly reproduced. The distinction is promising for interpretation; laboratory experiments are here available, and give hope of a solution to the problem. Yet it still in a manner evades our grasp. Physicists are not agreed as to how the signs they register should be read. Something will be said in a future Chapter about their tentative conclusions.

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CHAPTER IV

THE CHEMISTRY OF RED STARS

NEARLY all stars of a pronounced red colour show spectra crossed by dusky bands of absorption. Two varieties can be at once discriminated. They respectively form Secchi's third and fourth types. Now spectra consisting of bands or flutings are given out in the laboratory by compound substances, such as oxides and chlorides, as well as by the chemical elements glowing at a low pitch of excitement. They were formerly thought to originate from molecular, line-spectra from atomic vibrations. But this opinion has been much shaken by recent experience.[1] Trowbridge and Richards concluded in 1897[2] that, where electricity is the illuminating agent, an oscillatory discharge gives rise to isolated rays, a "dead-beat" discharge to flutings. And it is easily understood that successive shocks of transmitted energy should evoke more intimate thrillings than an even flow. Electrical stimulation of any kind is not, however, necessary for the production of banded spectra; the cool oxygen of our own atmosphere stamps the red section of dispersed sunlight with three conspicuously dark flutings. Moreover, a profound difference in the relationships of the two kinds of spectra is signified by the insensibility of fluted emissions to magnetic influence. They evince no trace of a "Zeeman effect"; they remain unaltered and imperturbable in the field of the most powerful magnet. Pressure is similarly impotent to modify their wave-lengths or structure. They are, however, displaced by

[1] Deslandres, *Comptes Rendus*, t. cxxxvii. p. 1013, Dec. 14, 1903.
[2] *American Journal of Science*, vol. iii. p. 117.

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radial motion in the same manner, and to the same extent, as linear emissions.

Flutings are made up of numerous individual lines set more and more closely together towards the "head," and at continually widening intervals towards the "tail." They in fact constitute series, on the model of those of hydrogen and helium, but condensed into a much smaller space. The numerical formulæ representing the principle of their construction have, since 1885, been investigated with a fair promise of success, first by M. Deslandres,[1] later by M. Thiele.[2] Enough has been done to show that the arrangement both of bands in the same spectrum, and of lines in the same band, is methodical, and may eventually be rendered intelligible; but the underlying laws are too intricate for immediate and full recognition.

In the stars, fluting-absorption is superadded to absorption by lines. Metallic groovings, agreeing in position with those of the solar spectrum, but somewhat reinforced, as a rule, in strength, aid the interception of photospheric radiations dimmed further by a "smoky" envelope chiefly arrestive of the shorter wave-lengths. Thus, three distinct forms of absorption mark their effects in banded spectra, and seem to betray the action of deep and dense vaporous strata. Hence the redness of the stars. And, because their photographic rays are largely cut off, they come out on sensitive plates five or six times fainter than they appear to the eye. Their spectra, too, are recorded with much difficulty. In some, nearly all the violet, and all the ultra-violet, light is extinguished; while their blue beams are enfeebled by crossing a triple barrier of absorption. For purposes of effectual investigation, accordingly, orthochromatic plates have to be employed; and these are not free from inconveniences and drawbacks.

From Antares (*a* Scorpii), a remarkably fine specimen of the third stellar type, Sir Norman Lockyer has conveniently designated its members "Antarian stars." The flutings in their spectra terminate abruptly towards the violet, but shade

[1] *Comptes Rendus*, t.c. p. 1256; *ibid.* Oct. 17, 1904; Kayser, *Handbuch der Spectroscopie*, Bd. ii. p. 475.

[2] *Astroph. Journal*, vol. vi. p. 65, viii. p. 1.

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off gradually towards the red, producing to the eye something of a colonnaded effect. This, however, is lost in photographs; partly because the flutings are discontinued in the higher spectral ranges, partly because the general impression is overborne by the wealth of self-recorded details. All spectra of this kind are constructed on the same fundamental design. The principal bands, of which ten are counted, reappear with essential invariability in every Antarian star.[1] A homogeneous origin is thus suggested for them. It is unlikely that many substances, each acting independently of the others, are concerned in the weaving of a pattern widely diffused, and practically unchanging. Yet their chemical interpretation long remained a source of perplexity. Third-type absorption had no known analogue until Mr. Fowler, in 1904,[2] thought of comparing it with the flutings emitted by titanium oxide, rendered luminous by low-tension electricity. They were found to coincide very approximately with eight out of the ten star-bands; and particular resemblances in the arrangement of lines within the flutings emphasised the general agreement. Stellar spectra of the third type thus promise finally to yield up their secret; for it must be, at least provisionally, admitted that titanium plays a leading part in giving them their channelled aspect. Cyanogen flutings, too, have been photographed in these stars by Professor Hale and Mr. Ellerman;[3] but they are of shorter wave-lengths than any of the bands previously measured. They constitute a novel feature of uncommon interest, as the only symptom so far recognised of the presence of carbon, or its compounds, in third-type stars.

Aldebaran, although a solar star, is unmistakably of a reddish tinge. The blue end of its spectrum is heavily obscured; and the flutings characteristic of the type towards which it seems to be advancing are just indicated as embryonic shadings. The object might be called a linking instance between Arcturus and Betelgeux (α Orionis), in which titanium flutings (if we may so designate them) are fully developed, while the main features of the Fraunhofer spectrum remain unaltered and uneffaced. The least possible departure is made

[1] Dunér, *Sur les Étoiles à Spectres de la Troisième Classe*, p. 8.
[2] *Proc. Royal Society*, March 8, 1904.
[3] *Spectra of Fourth-Type Stars*, p. 116.

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from the solar model that is reconcilable with the complete presentment of a different type. By comparing Plate II., Fig. 4, with Plate III., Fig. 2, our readers can estimate the closeness of the analogy between the linear elements in the spectra of Capella and Betelgeux. The four lowest lines of hydrogen are fairly strong in Betelgeux; but in specimens presumed to be more "advanced" they thin out, and perhaps disappear with the closing in of dense banded absorption. A fine red star in the Southern Cross, γ Crucis, is of nearly the same standing as Betelgeux; in α Herculis the bands have acquired strength through the efflux of time, it is supposed, and the progress of cooling.

Eight or nine metals are easily recognisable by their absorption-lines in Antarian spectra. Calcium is the most prominent. The notable pair of diffuse stripes in the violet due to it are fully the equals of their archetypes in the sun; while the flame-line in the blue, λ 4227, shown as a black bar bisecting the spectrum in Plate IV., Fig. 2, is of greatly augmented intensity. Iron comes next to calcium in effectiveness for light-stoppage; and with it are associated magnesium, sodium, chromium, titanium, vanadium, aluminium, strontium, and probably manganese. No lines distinctive of the electric spark are present; but those widened in sun-spots stand out significantly.

Red stars, as we have said, are encompassed with powerfully absorptive atmospheres; and atmospheric density and extent are, for some recondite reason, accompanied by instability in shining. The radiative machinery tends to become clogged fitfully, or at definite intervals, and irregular or periodical variability results. Nor do the spectra of Antarian stars remain unaffected by these vicissitudes. Their continuous radiance brightens and fades unequally in its differently refrangible sections, though according to no traceable method; the bands interrupting it alternately close in and thin off; above all, vivid rays of hydrogen and other substances are kindled with the recurrence of the brilliant phases, and die out as each fresh outburst of energy becomes exhausted. This striking feature was first detected in a spectrogram of Mira Ceti taken at Harvard College in 1886; and scores of "long-period variables" have since, through Mrs. Fleming's

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researches, been recognised by their exhibition of the same peculiarity. Only two of them, however, have as yet been at all adequately studied. Mira has been made the subject of some admirable investigations at the Lick Observatory; and χ Cygni has been dealt with to good purpose at Potsdam during some of its recent maxima.

The character of the spectrum of Mira is well shown in Plate IV., Fig. 2, reproduced, by the kind permission of Professor Pickering, from a Harvard photograph. The two blue hydrogen-rays ($H\gamma$ and $H\delta$) emerge resplendent; yet the green and violet lines ($H\beta$ and $H\epsilon$) are alike imperceptible; while four of the ultra-violet sequence shine brilliantly. Professor Campbell ascertained by direct observations with the great Lick refractor at the high maximum of 1898, that the crimson hydrogen-line makes no show in this star.[1] Nevertheless, in vacuum-tubes, in the solar chromosphere, and in bright-line helium stars, C is the most vivid member of the series. In nebulæ, on the other hand, it is usually invisible; and thus the unexpected conclusion is forced upon us that hydrogen glows in the great irregular nebulæ under similar conditions of excitement to those prevailing in variable Antarian stars. The suppression of the fifth line ($H\epsilon$) is universal in such objects, and was believed to be complete until the missing radiation faintly recorded itself on some of the spectrograms of Mira lately secured by Messrs. Wright and Stebbins at Lick. It seemed to glimmer through a dense layer of calcium, the nearly coincident absorption of which in general masks it effectually. This explanation, however, needs to be further verified. It has much to recommend it; yet it involves an inversion of the order of stratification, as regards emitting and absorbing vapours, commonly observed in stars.

The tripling of the hydrogen-lines in Mira, noted by Professor Campbell in October 1898, is highly suggestive of magnetic action. But the effect, though eagerly looked for, has not since recurred, and appears to betoken exceptional agitation. On the same occasion, two iron-lines, previously registered as dark, came out conspicuously bright; and they were again brightened at the maximum of 1902, together with a number of others, including the principal arc-line

[1] *Astroph. Journ.* vol. ix. p. 36.

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of silicon at λ 3906. Mr. Joel Stebbins[1] followed the star spectrographically down to a minimum at ninth magnitude in January 1903, when a six hours' exposure barely sufficed to procure a legible, though not a measurable impression from rays shorn of the adventitious glory lent to them by transitory gaseous incandescence. The phenomena attending the brilliant phases of χ Cygni, as observed by M. Eberhard,[2] are essentially similar to those displayed by Mira.

About 15 per cent of third-type stars are established variables; and few shine with the constancy of an average white star. Moreover, those subject to the widest vicissitudes have, on the whole, spectra the least like that of the sun. They seem to have descended furthest along an inclined plane of change, for there is no evidence of abrupt departures from what was presumably the more primitive type. The distinctions between our sun and a Mira-variable, though strongly pronounced, may have been brought about by insensible gradations; and the inference invites, if it do not command our assent that no halt can be cried in the evolutionary journey from a stable condition of sun-like luminosity to the stage of turbulent incandescence marked by the ruddy flare of recurrent maxima.

The spectra of fourth-type, or "carbon-stars," resemble those of the Antarian kind in being marked by linear, as well as by banded absorption. Their aspect to the eye is illustrated in Plate IV., Fig. 3, copied from M. Dunér's drawings by permission of the University Press of Chicago. From the first, Father Secchi recognised the carbonaceous origin of the three deep shadings, distinguished in the Figure as B6, B9, and B10. They face redward (to the right), and match respectively the yellow, green, and blue flutings of the so-called "Swan" spectrum, derived, according to some authorities, from pure carbon—according to others, from carbon monoxide. But these stars are, without exception, faint; the brightest is of 5·3 magnitude; and beyond the presence of some strong lines due to iron and sodium, little further could be learned about them until more powerful optical means became available. The completion of the Yerkes 40-inch refractor at last

[1] *Astroph. Journ.* vol. xviii. p. 341.
[2] *Ibid.* vol. xviii. p. 202.

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supplied the needed facilities; and in 1898 Professor Hale, assisted by Mr. Ellerman, undertook the spectrographic investigation of fourth-type stars. Their overwhelming self-absorption in the blue made the task seem unpromising; but by the employment of isochromatic plates of different quality for the several spectral sections, together with exposures up to twenty-four hours in duration, it was successfully executed. The definite results, published in 1903, are of the utmost value.[1] They refer more particularly to eight stars, the designations and places of which are as follows:—

Name.	R.A. (1900).	Dec. (1900).	Mag.
74 Schjellerup . . .	6h 19m 46s	+14° 47′	6·5
78 Schjellerup . . .	6 29 40	+38 32	6·3
115 Schjellerup . . .	8 49 45	+17 37	6·5
132 Schjellerup (= U Hydræ) .	10 32 36	−12 52	6·5 (var.)
318 Birmingham . . .	10 38 8	+57 56	6·4
152 Schjellerup . . .	12 24 26	+45 59	5·5
19 Piscium	23 41 17	+ 2 56	5·3 (var.)
280 Schjellerup . . .	23 56 10	+59 48	7·8

Of the above, six are known by their numbers in a *Catalogue of Red Stars*, drawn up by the Danish astronomer Schjellerup in 1866; one is taken from a similar work by John Birmingham of Tuam, dated ten years later; and the eighth and brightest was enrolled by Flamsteed. On the Yerkes plates of their spectra no less than 307 dark lines were measured, and in part traced to their origins. They indicated the undoubted action of ten substances, namely, hydrogen, calcium, titanium, vanadium, iron, sodium, magnesium, chromium, nickel, and manganese, and suggested that of others. The record of cyanogen-flutings in the blue (see Plate V.) constituted in itself an important gain to knowledge; and still more the discovery that bright lines are profusely scattered among the dark elements of such spectra. This had been to some extent perceived by Father Secchi; but his observations were only rescued from the discredit into which they had fallen by the sure testimony of the camera. At present some two hundred rays of emission have been

[1] *Decennial Publications of the University of Chicago*, vol. viii., from which Plate V. is reproduced, by the courtesy of the University Press authorities.

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determined in carbon-stars, although one only has been securely identified. This is the hydrogen-F, which at times (for its condition is subject to change) shines conspicuously in the peculiar star 280 Schjellerup (see Plate V., uppermost spectrum), and more dimly in a few other members of the class; while, in 19 Piscium, the blue and indigo hydrogen-lines are dark, and no trace of F, bright or dark, is to be found. Of the remaining crowd of vivified rays, some may be due to oxygen and nitrogen, one coincides with the fundamental member of the Pickering-series of hydrogen, and three or four besides fall very near emission-rays in gaseous stars of the "Wolf-Rayet" variety. On the other hand, the absorption-spectra of carbon-stars are extensively composed of lines widened in sun-spots; the metallic spark-lines characteristic of early stars have vanished from them, and been replaced by arc and flame-lines, held to be an unfailing symptom of advanced stellar age; and it is associated with variability in light even more pronounced than that shown by Antarian stars. Professor Hale's general conclusion is that third- and fourth-type stars "should be classed together as co-ordinate branches leading back to stars like the sun," from which they probably develop through loss of heat by radiation.[1] That is to say, an outworn solar star may descend to extinction by either of these alternative downward paths. But why one is chosen rather than the other remains obscure.

Two circumstances are, however, adverse to the view that suns like our own are liable to degrade into carbon stars. The first is the lack of intermediate specimens. Professor Hale urges the plea often put forward by embarrassed palæontologists, that the record is incomplete; and it may well prove valid. He has already picked up some stray connecting links, and it would be premature indeed to despair of more being found. But there is another very serious difficulty. It relates to the distribution of the stars. Those of the fourth type are strongly condensed towards the Milky Way.[2] Their relations to the fundamental plane of the sidereal system are quite different from those of solar stars. More-

[1] *Decennial Publications*, vol. viii. p. 135.

[2] Dunér, *Spectres de la Troisième Classe*, p. 126; Parkhurst, *Astroph. Journ.* vol. ix. p. 239; Espin, *ibid.* vol. x. p. 169.

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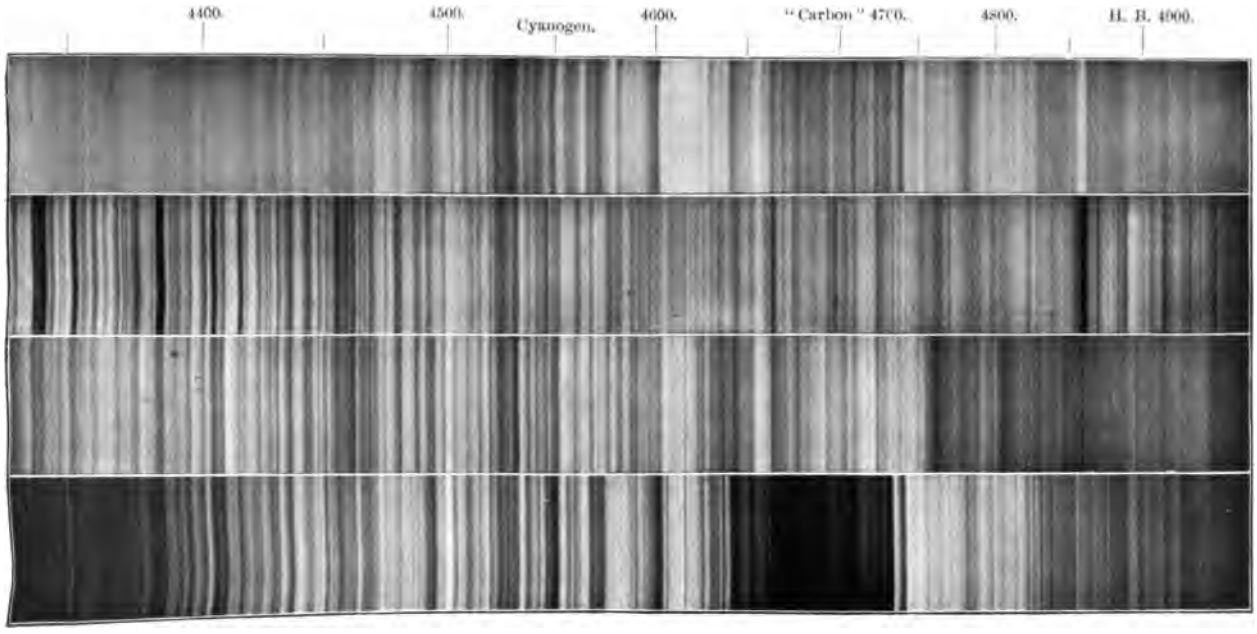

Stellar Spectra of the Second, Third, and Fourth Types in the Blue Region. Photographed by Hale and Ellerman.
(From Decennial Publications of the University of Chicago.)

PLATE V.

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over, they are evidently extremely remote. They seem to occupy a region of space apart from that tenanted by our sun and his congeners. The incongruity is then obvious of supposing that they are united with them in a single evolutionary series.

About 250 carbon stars have, so far, been registered. Many were detected visually by Mr. Espin; but Mrs. Fleming's photographic gleanings have contributed largely to swell the total. Seven out of the 250 can just be seen with the naked eye; the rest are telescopic objects. One of the finest specimens is Secchi's "La Superba" (152 Schjellerup), situated in Canes Venatici. It was so entitled for the extraordinary vivacity of its prismatic rays, separated into dazzling "zones," red, yellow, and green, by broad spaces of profound obscurity. This star shines with approximate constancy; 19 Piscium at times surpasses it in brightness, but is subject to temporary deprivations of more than one-half its light. These happen irregularly; many periodical variables, however, belong to the same spectral type, among them U and V Cygni, S Cephei, V Hydræ, and R Leporis, noticed by Hind for its intense crimson colour.

The comparative dimness of all such objects, though doubtless in part due to their great distance from the earth, is readily explicable by the opacity of their atmospheres. How much of their intrinsic light escapes absorption can only be conjectured; if we put it at a tenth, our estimate is likely to exceed rather than fall short of the truth. Only loopholes, so to speak, are left for its exit; and, as usual, the violet and blue rays suffer most severely, being indeed almost completely smothered. The special depth of colour in carbon stars is thus accounted for. They are not merely suffused with red, like Betelgeux and Antares; they actually simulate the glow of carbuncles or rubies in the field of the telescope. Vast and magnificent orbs must be found among them. Under circumstances less disadvantageous, some might well take rank in the second magnitude of Sirian and solar stars; and this apart from any allowance for their apparently exceptional remoteness. The final darkening and death of fourth-type stars may then be reckoned as a contingency too far off for definite realisation.

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CHAPTER V

GASEOUS STARS AND NEBULÆ

GASEOUS stars form a restricted and peculiar class. The objects belonging to it are characterised by the display in their spectra of isolated bright and dark lines on a more or less perfectly continuous background. They present us then with a triple combination—a *direct* gaseous spectrum, a *reversed* gaseous spectrum, and a spectrum due to glowing solid or liquid matter, all simultaneously made manifest by the unrolling of a single scroll, yet each originating under very different conditions. The true discrimination of those conditions tasks all the resources of physical sidereal astronomy.

The state of bright emission is in some stars normal, in others it only supervenes as part of a great general increase of light. It is not limited to any one period of sidereal existence. Stars barely condensed from nebulæ sometimes show bright lines, and the symptom is (as we have seen) apt to recur at the advanced stage reached by red stars with banded spectra. Only Sirian and solar stars are exempt from the tendency; helium stars are peculiarly liable to it. It would thus seem that the stars capable of yielding mixed spectra of absorption and emission are those either unfinished or verging towards decay, while, during the intermediate epochs of vigorous maturity, absorption is alone effective. The term "gaseous," however, should be reserved for inchoate orbs. Those giving bright lines are probably distended far beyond the solar proportion of size to mass; and their spectra bear the distinctive marks of helium, frequently of cosmic hydrogen, and not rarely of oxygen and nitrogen.

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They have the further distinction of showing the ordinary hydrogen-series—the Huggins-series—in duplicate, a bright line being coupled with, or superposed upon, a dark one of identical origin; and the rule first adverted to by Professor Campbell[1] is invariable that, under these circumstances, absorption becomes stronger, and emission feebler with diminution of wave-length. The brightest lines, in other words, are the least refrangible. Alcyone in the Pleiades is an example. In this star one solitary ray is vivid, and it is the fundamental C (Hα), which glows crimson beside a dark companion. Pleione in the same group, on the other hand, and many stars besides, exhibit the direct radiance of several members of the hydrogen-series; but that of C always predominates. Similarly in the various helium-series, the stress of brightness is inevitably laid upon the lowest of their constituent lines. But to make this apparent, the series must be sorted out; for the rule applies to each individually. An analogous order of progression was subsequently found by Professor Hale to regulate the reversal of lines in metallic spectra.[2] As the vapours rendered incandescent by the electric spark taken under water became more and more self-absorptive, he perceived that the lines progressively darkened descended the scale of refrangibility with approximate steadiness. That is to say, the rays most persistently bright were those of greatest wave-lengths. Here, undoubtedly, we hold a clue to the physical state of emissive stars, but one, unfortunately, by no means easy to follow up.

The first specimen of a gaseous star was made known by Father Secchi's discovery, August 19, 1866, of the green line (F) of hydrogen conspicuously bright in γ Cassiopeiæ,[3] the middle star of five of the second and third magnitudes grouped into the shape of a W on the opposite side of the pole from the Great Bear. Soon afterwards the same peculiarity revealed itself in β Lyræ, the emission being discerned in it as well as in γ Cassiopeiæ of three rays of hydrogen and one of helium. But these do not always present the same appearance. As early as 1872 Vogel was struck with

[1] *Astroph. Journal*, vol. ii. p. 181.
[2] *Ibid.* vol. xv. p. 227.
[3] *Sugli Spettri Prismatici delle Stelle Fisse*, Mem. i. p. 10, Mem. ii. p. 62.

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their apparently unaccountable caprices of visibility;[1] and M. von Gothard watched vainly during two years before he caught sight in γ Cassiopeiæ of the crimson twinkling of C *in particularly unfavourable weather*, August 13, 1883.[2] His subsequent observations, and those of M. von Konkoly,[3] fully established the occurrence, in both stars, of remarkable spectral fluctuations, which have since been studied, with attentive curiosity, in widely separated parts of the world.

The result has been to establish their reality, but strongly to discriminate between the modes of their occurrence in the two objects. They are periodical in β Lyræ, and their period is that of the star's light-change. The flickering of bright lines in its spectrum, accordingly, depends in some way upon the rise and decline of its visual luminosity.[4] But the white radiance of γ Cassiopeiæ, although including variable elements, is, in its sum-total, perfectly steady. Since the advent of spectrography, fluctuations in the hydrogen-lines have ceased to be apparent; but then C, which lies below the range of the sensitive plate, has scarcely of late been looked for. And C was precisely the line most noted, in the days of visual observation, for capricious shining. This property is unmistakable in the yellow helium-ray (D_3); the sodium-absorption near it is also apt to become effaced; and the green and blue magnesium lines appear, with unaccountable alternations, bright and obscure. Nor is it at present known whether these sundry changes proceed in concert, or each on its own account.

The spectrum of μ Centauri, which closely resembles that of γ Cassiopeiæ, is represented, from a photograph taken at Arequipa, February 8, 1897, in Plate III., Fig. 3. The brilliant line to the right is Hβ (F); but the dusky edges, faintly perceived to fringe it on the original negative, are swallowed up, in the print, by the general gloom due to the idiosyncrasy of the plate. The lustre of Hγ is, however, strongly relieved by corresponding absorption, and Hδ displays merely a thread of light dividing a profoundly dark band. Two clean cut, black lines to the right of Hγ

[1] *Bothkamp Beobachtungen*, Heft ii. p. 29. [2] *Astr. Nach.* Nos. 2531, 2589.
[3] *Observatory*, vol. vi. p. 332; *O Gyalla Beobachtungen*, vol. viii. p. 5.
[4] See Chapter XXI. of *Problems in Astrophysics* by the present writer.

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originate from helium; and there is room for further research in the identification of many additional rays, both bright and dark, in this beautiful spectrum.[1] Professor Campbell, in 1894, observed in it the crimson shining of C. No suspicion of variability attaches to the star.

A star-disc is rendered through distance immeasurably small. It has no longer diversified parts. The light from all is blended indiscriminately into the radiance of a single point. Hence, Dr. Scheiner argued, the mere increase of atmospheric extent, apart from any increase of atmospheric emissive intensity, would give overweening effectiveness to the bright-line ingredient,[2] an insignificant proportion of which is present in the luminous sheaf sent out by ordinary stars. Experience has, however, virtually negatived this view. The phenomena of spectral variability are entirely irreconcilable with it. And, in one form or another, they prove to be widely diffused. But the absurdity is patent of invoking fluctuations in atmospheric compass to account for them. The gaseous surroundings of stars may conceivably be subject to changes of luminosity; but the hypothesis of their expansion and contraction with the rapidity, and to the vast extent required, is plainly inadmissible. Moreover, the diversity of conditions under which bright lines are perceived to originate, their complex reversals, their peculiar individualities, intimate the working of profound physical agencies, and repudiate any single formula of explanation incapable of adaptation to the lavish variety of nature.

Dr. Schuster proposed, in 1903, a theory in some respects preferable to Scheiner's. Both speculators alike sought to evade the direct consequence of Kirchhoff's Law, according to which, "a layer of gas in front of a radiating surface can only give bright lines if its temperature be higher than that of the radiating surface";[3] a state of things not easily to be supposed existent in stellar or solar atmospheres. A new expedient was accordingly resorted to by Dr. Schuster. He showed that bright lines might be produced by the dispersion of light in layers of incandescant vapours overlaying a hotter radi-

[1] Cf. Lockyer and Baxendall, *Month. Notices*, April 1905, App. No. 2.
[2] Scheiner, *Die Spectralanalyse der Gestirne*, p. 276.
[3] *Observatory*, vol. xxvi. p. 379.

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ating surface. His reasoning is no doubt correct, and we have here a "true cause," although scarcely one that is sufficient for the part assigned to it. Its inadequacy becomes patent when we consider that its action is at a minimum just where the effects attributed to it are most conspicuous. The scattering power of pure gases must be very small compared with that of the vapours, say, of carbon, silicon, or titanium. Yet the bright lines in stellar spectra are chiefly those of the tenuous and translucent gases, hydrogen and helium. The rationale is thus unconvincing.

Another, designed expressly to meet the case of temporary stars, has been advanced by M. Ebert.[1] It is based upon the principle of "anomalous refraction," by which light subtracted, through a special action of the refracting medium, from one narrow section of the spectrum, goes to reinforce the adjacent strip, a show of paired bright and dark lines appearing as the result. But here, again, the actual phenomena seem recalcitrant. Hydrogen and helium are among the least refractive of substances. They are eminently unlikely to act on transmitted radiance in the forcible manner demanded by M. Ebert's theory.

The stellar class, of which γ Cassiopeiæ is typical, has now upwards of fifty known representatives, most of them having been detected by Mrs. Fleming on the Harvard spectrographic plates. Among them are the noted ex-variables, at present shining with an uniform, unpretentious lustre, η Carinæ and P Cygni. The spectrum of the former object was found by Sir David Gill to bear a strong resemblance to that of Nova Aurigæ;[2] and P Cygni is similarly characterised. The permanence in both of spectral relations transient in new stars has an import which can hardly be over-emphasised.

The so-called Wolf-Rayet species of gaseous stars, although cognate with the helium variety, stands well apart from them. Hydrogen and helium rays are, in their spectra, of subordinate importance. They are mainly distinguished by certain vivid bands in the yellow and blue, some of them due to cosmic hydrogen, others of untraced origin.

[1] *Astr. Nach.* No. 3917.

[2] *Monthly Notices*, vol. lxi. p. 456. See also A. J. Cannon, *Harvard Annals*, vol. xxviii. part ii. p. 175.

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The finest specimen of the class is invisible in these latitudes. First detected by Respighi at Madras, December 24, 1871,[1] the peculiarities in the light of γ Velorum were studied with some care and much delight at the "extraordinary beauty" of the spectacle they present, by Dr. Copeland at Puno in the Andes, April 24, 1883.[2] "An intensely bright line in the blue," he remarked, "and the gorgeous group of three bright lines in the yellow and orange, render the spectrum" of this star "incomparably the most brilliant and striking in the whole heavens." There is no sign that it is in any degree variable. Its appearance to the present writer, at the Cape, in October 1888, tallied precisely with Dr. Copeland's description, only that the additional feature of a deep band of absorption below the cobalt line seemed unmistakable.[3] A vivid continuous spectrum extends into the violet as far as the eye has power to follow it, and accounts for the brilliant whiteness of the star. The diffuseness of radiation in this splendid object is an obstacle to its effective spectrographic treatment. A fair idea of its character can, however, be gathered from Plate III., Fig. 4, which reproduces, by the courtesy of Professor Pickering, a photograph taken at Arequipa with 99 minutes' exposure, April 28, 1897. It does not extend to the lower tract illuminated by the golden and citron rays. The spectrum begins on the right with the double or triple azure bands distinctive of this stellar type. The less refrangible (λ 4688) occupies a remarkable position. It is that theoretically assigned by Rydberg in 1897 to the one member accessible to view of the "principal series" of hydrogen. By analogy it should be there, and it is. This azure band seems to be an unfailing adjunct to the Pickering series, which it imitates as well by refusing to be evoked in the laboratory. Professor Campbell was surprised, in 1893, to find C brilliant in the spectrum of γ Velorum, the other hydrogen lines being dark.[4] They are nevertheless perceived photographically as projected on bright bands, an arrangement the inverse of that prevalent in

[1] *Comptes Rendus*, t. lxxiv. p. 516.
[2] *Copernicus*, vol. iii. p. 206.
[3] *Observatory*, vol. xi. p. 430.
[4] *Publications Astr. Pac. Society*, vol. v. p. 106.

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gaseous stars of the helium kind.[1] Absorption by oxygen was detected by Mr. McClean amid the emissive splendours of the southern luminary; metallic action is probably absent throughout the class which it exemplifies.

Its original members, three small stars in Cygnus, have, in the course of thirty-eight years, obtained about one hundred associates, largely through the extensive photographic researches of Mrs. Fleming. All these are situated in the throng of the Milky Way, or of the Magellanic Clouds; and all, except γ Velorum, are insignificant when casually regarded. None are known to vary in light; in none, so far, has any spectral change been recorded. Individual diversities, however, abound. Lines dark in one specimen may be bright in another; bands are more or less hazy; the blue effluences differ from star to star in relative strength; hydrogen and helium lines are now prominent, then again of quite subordinate importance. One such star was discovered by Campbell to possess a vast hydrogen-envelope, indicated as existent only by the sensible length of the green ray originating from its glow. Perhaps some of its fellows have similar, if less conspicuous appurtenances; though none of them are, in the proper sense, nebulous, since they give sharp images, telescopically and photographically.

Yet, in the Wolf-Rayet stars, we have undoubtedly reached the borderland between the two great sidereal kingdoms, where definitions cease to be valid, distinctions become insecure, and nondescript characters perplex classification. Between gaseous stars and stellar nebulæ there is but a narrow gap. Individuals of both species present the telescopic appearance of small stars; and they disclose, when a prism is applied, analogous peculiarities—analogous, not identical. The light of a gaseous star so examined is ordinarily concentrated in two points, or where a cylindrical lens is employed in two short lines, yellow and blue respectively; that of a stellar nebula gathers into one green knot. Its rays are, in a sense, incapable of analysis; they are so nearly monochromatic that they can be refracted without being dispersed. Objects of this nature can be picked out at a glance from ordinary stars by Professor Pickering's method of "sweeping" with a

[1] A. J. Cannon, *Harvard Annals*, vol. xxviii. p. 247.

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small direct-vision spectroscope used as an eye-piece.[1] Above a score of them were in this manner found previously to 1890, and many more subsequently by photographic means; and it is remarkable that the exclusive preference for the Milky Way of gaseous stars is shared by stellar nebulæ.

The green ray of the latter is the characteristic token of gaseous nebulæ. From the great Orion "portent" to the faintest "planetary," all without exception show it; and in many it appears at first sight so predominant as virtually to stand alone. But its origin remains an enigma. In position it is almost coincident with an important line of nitrogen. A trifling divergence, however, shows them to be certainly distinct. Nor can it be identified, as Sir Norman Lockyer thought it might, with the sharp edge of a fluting emitted by magnesium burning at about the temperature of the Bunsen flame.[2] The supposed agreement was made the corner-stone of the meteoritic hypothesis of nebular constitution;[3] but it failed to obtain ratification by precise inquiry.

Careful measurements by Sir William and Lady Huggins,[4] and by the late Professor Keeler, showed the fundamental meteoric and nebular lines to stand very slightly apart in the spectrum. But spectroscopic agreements must be absolute if they are to be reckoned significant. Moreover, the nebular line is sharp; and even the thinnest remnant of a fluting should have an attachment of unilateral haze.

Nebular radiance cannot then, it seems, be imitated in the laboratory. Possibly it signalises a modification of matter arising only under extra-terrestrial conditions. "Nebulium," as the hypothetical element is called, has been vainly sought amongst the mixed leavings infinitesimally separated from common air by intense refrigeration, under favour of their unequal boiling-points; no mineral, however scarce, has been discovered to occlude it; no volcanic vent exhales it. Yet it fills whole tracts of galactic space. Must we then admit, after all, that there is a chemistry transcending text-books? It may be so; but to abandon the grand ideal of an universal

[1] Pickering, *Observatory*, vols. iv. p. 81; v. p. 294; *Astr. Nach.* No. 2517; Copeland, *Monthly Notices*, vol. xlv. p. 91.

[2] *Proc. R. Society*, vol. xliii. pp. 124, 127.

[3] *Ibid.* vol. xliv. p. 2.

[4] *Ibid.* vol. xlvi. p. 48.

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physical science because of a few outstanding incongruities would be to listen half-heartedly to counsels of impatience. Stellar nebulæ, so far as can be judged, are excessively remote, voluminous, faintly glowing bodies. The condensed or nuclear portions probably included in them give but slight signs of incandescence; spectroscopically (whatever they may be physically) they are mere spheres of glimmering gas. Now planetary nebulæ (so called by Sir William Herschel because they exhibit a planet-like disc) scarcely differ intrinsically from the stellar sort, but they either are, or owing to their greater vicinity, appear larger and brighter, and hence offer better facilities for the analysis of their light.

It is found to consist mainly of three rays composing the fundamental spectrum of all gaseous nebulæ. Of these, the lowest, of wave-length 5007, is invariably the strongest, and accordingly survives alone in such a dearth of light as that created by the combined distance and faintness of the monochromatic discs or points detected by Professor Pickering's method.

The nebular trio of lines, since they lie adjacent to each other in the middle or green part of the spectrum, inevitably give a resultant green or bluish colour to the objects they characterise. The intermediate ray at λ 4959, as well as the chief ray, is plausibly connected with nebulium since it preserves in each individual nebula the same relative intensity. The third or most refrangible line, on the contrary, is independently faint or bright. It is no other than the familiar F (Hβ); and the undoubted and unfailing presence of hydrogen betokened by it in these formations constitutes one of the very few links as yet recognised between nebular and terrestrial chemistry. From the former metallic elements are excluded; they are, in nebulæ, either non-existent or non-apparent. And we recall that stars supposed on other grounds to be in a primitive condition are just those in which metalloids tend spectroscopically to suppress metals.

Modern appliances, spectroscopic and spectrographic, have enriched the nebular spectrum with some three dozen extra lines, mostly in the ultra-violet. Some of those derived from planetary nebulæ agree with lines bright in Wolf-Rayet stars, notably with the fundamental member of the Pickering series,

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and with the Rydberg blue band.[1] Occasionally, a glint of red hydrogen is seen; eight of its more refrangible companions have been measured; and helium is represented by a somewhat arbitrary selection from its various series.

The spectrum of the great Fish-mouth nebula in Orion was first adequately studied by Sir William and Lady Huggins from 1882 onwards. Its hydrogen-ingredient is in the peculiar condition denoted by its emission of the higher members of the Huggins series, C being imperceptible. The yellow ray of helium was detected by Dr. Copeland, December 28, 1886;[2] and he remarked "some indications of resolvability into lines or bands" in the dim prismatic background upon which the central group of rays in this spectrum are relieved. The opinion further expressed by Sir William and Lady Huggins that the faint continuous spectrum visible in most gaseous nebulæ might, were more light available, "be found to consist, in great part at least, of closely adjacent bright lines"[3] has been strongly confirmed by recent Lick spectrograms taken with the Crossley reflector, exhibiting tell-tale breaks and symptoms of overlap in the hazy radiance previously assumed to be of "white," or unbroken quality.[4] On a plate exposed at Tulse Hill in 1882, an intense ultra-violet ray of wavelength 3727 was recorded,[5] and it has proved to be almost as marked a feature of the nebular spectrum as the "chief" line itself; nor can it be an emission of nebulium, since its intensity varies disparately from that of the green lines.[6] It is singularly prominent in the Ring nebula in Lyra.

A gaseous nature was suggested for the four bright stars grouped into a "trapezium" at the core of the Orion nebula by an abnormal photograph taken by Sir William and Lady Huggins, February 5, 1888.[7] Several years later,[8] they perceived the hydrogen-lines to be not only arranged in bright and

[1] Copeland, *Copernicus*, vol. i. p. 2. The original "four-line" planetaries are numbered in Dreyer's New General Catalogue, 7662, 7026, and 7027. The two last belong to a singular group of allied gaseous objects in Cygnus.

[2] *Monthly Notices*, vol. xlviii. p. 360.

[3] *Proc. R. Society*, vol. xlvi. p. 60.

[4] *Lick Bulletin*, No. 35.

[5] *Report Brit. Association*, 1882.

[6] *Astroph. Journal*, vol. xxi. p. 398 (Hartmann).

[7] *Proc. Roy. Society*, vol. xlvi. p. 40.

[8] *Astroph. Journal*, vol. vi. p. 322.

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dark pairs, but to undergo shiftings defined by Professors Frost and Adams[1] as periodic in the chief member of the group, and dependent upon rapid orbital circulation. These stars are of the early helium variety; they show absorption by oxygen[2] and cosmic hydrogen; and it is an open question whether the bright lines crossing their spectra may not be derived from the folds of nebulous matter enwrapping them.

Local variations in the spectrum of the Orion nebula are most likely to subsist. It can hardly be supposed that so vast and so agitated a formation can be throughout of uniform composition. Professor Campbell, accordingly, found in 1893 that the relative intensities of the three lines, "which constitute nearly the whole of the visible spectrum, vary within wide limits as the slit of the spectroscope is moved over the different parts of the nebula."[3] That is to say, the two first lines, while preserving to each other a constant ratio, fluctuate largely by comparison with the third or hydrogen-line. In some sections of the nebulous structure, in fact, the hydrogen appears at least five times stronger than the nebulium-ray, although near the trapezium it is four times fainter. Hydrogen-light, in conjunction with the unidentified ultra-violet emanation, thus tends to become predominant with the decline of illuminative power, whence the conclusion may reasonably be drawn that the nebula verges more and more, with the increase of tenuity upward and outward, towards an almost purely hydrogenous composition.

And this serves to remind us that the spectra of the great nebulæ, like those of "zoned" stars, must be considered as integrating the results of emissions taking their rise under notably diverse circumstances. Innumerable strata of nebulous matter are piled one upon the other in the same line of sight. The eye is impotent to discriminate between them; even the spectroscope can do so only indirectly. For, at the centre of the nebula, the lines coming from all its depths are seen or photographed together; their different places of origin

[1] *Astroph. Journal*, vol. xix. p. 153.

[2] McClean, *Phil. Trans.* vol. cxci. p. 128.

[3] *Publ. Astr. Pac. Society*, vol. v. p. 206; *Astr. Nach.* No. 3471; cf. Runge on the physiological variations of brightness due to difference of colour, *Astroph. Journ.* vol. viii. p. 32.

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are unnoticed. Light, on the other hand, taken from near the edges of the same object, emanates exclusively from its higher regions, and its characteristic peculiarities may safely be localised. The possibility then seems at hand of dividing in this way the Orion nebula and others of the same class into various spectroscopic levels, distinguished by minor radiative differences. The helium-lines, for example, may prove separable from the hydrogen-lines; and it would be especially interesting to ascertain whether the three hydrogen series change their relative intensities with remoteness from the trapezium. The differing conditions along the same line of sight must also hamper attempts to determine the internal movements of the nebula by the displacements or distortions of its spectral rays. For there must be a wide discordance in these effects at the heights and hollows projected together by perspective. Opposite motions might be progressing in the sundry regions conjointly inspected; and the upshot would be an ambiguous blurring of lines. Such a possibility must be taken into account in estimating the value of some promising experiments of this nature made by Drs. Vogel and Eberhard at Potsdam in 1902.[1] They hinted at tumultuous flows, or eddies, more probably than at a general rotation. But until they have been repeated and confirmed, it would be vain to speculate upon what they seem to communicate.

Only the species designated as stellar, planetary, annular, and irregular nebulæ give unmistakable signs of gaseity. Some five or six score have, up to the present, been recorded to do so; while several hundreds, and presumably the majority of those unobserved, shine with continuous light. Yet the distinction is perhaps less profound than it seems. The gap is at any rate partially bridged. One connecting link seems to be supplied by the great "looped nebula" in the southern constellation of Dorado, observed by Mr. C. E. Burton[2] in 1874 to yield a strongly continuous spectrum crossed by the unfailing green nebular ray at 5007. Its gaseous nature is thus shown to be modified by the presence of an unusually large proportion of dense material, and where this predominates, as in the Andromeda nebula, the spectrum,

[1] *Sitzungsberichte*, Berlin, March 13, 1902.

[2] *Monthly Notices*, vol. xxxvi. p. 69. See 47th *Harvard Report*, p. 7, 1892.

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though nominally "continuous," is still markedly different from the continuous spectrum of a star.

The light of this "queen of the nebulæ," prismatically dispersed for the first time by Sir William Huggins in 1864, struck him as far from uniform; it seemed *mottled* throughout, whether by the effects of absorption or of irregular emission, it was impossible to decide.[1] Recent observations at Tulse Hill point to the existence in this spectrum of various bright lines or spaces intermixed with traits of absorption.[2] Dr. Scheiner performed in 1899 the difficult feat of spectrographing the object, which he inferred, from the faint indications on his plate, to be a cluster of solar stars.[3] The truth of the matter remains still hidden; but there are signs that it can before long be elicited. In the investigation of the distinctive peculiarities of continuous nebular light, a field lies open which can hardly fail to be worked with profit to the rapidly advancing science of cosmical physics.

[1] *Phil. Trans.* vol. cliv. p. 441.
[2] *Atlas of Stellar Spectra*, p. 125.
[3] *Astr. Nach.* No. 3549.

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CHAPTER VI

THE TEMPERATURES OF THE STARS

WHAT we mean by the temperature of a star is the degree of heat corresponding, on admitted principles, to the radiations it sends abroad into space. That is to say, the point at which an ideal thermometer would stand if placed within the photosphere, assumed for the purpose of simplification to be effectively a single emitting surface. Now, the temperature of the sun, understood in this sense, has been fairly well ascertained. It is held by the latest authorities not greatly to exceed 6000° C, while that of the electric arc, determined by similar methods, comes up to 4000°.[1] Thus, the gap dividing the heat of the solar furnace from the *ne plus ultra* of the laboratory has been greatly narrowed. It no longer seems hopeless to establish some degree of continuity between the state of things on either side of it. Nevertheless, there are qualifications to be taken into account. Conclusions regarding the sun's temperature depend essentially upon two conditions: first, that the photosphere is what is technically known as a "black body"; next, that "Stefan's law" of radiation holds good over a range some thousands of degrees beyond the limit of experimental verification. Now, a "black body" is one that absorbs completely, and, through an inevitable correlation, emits perfectly. It radiates in the strict and due proportion of the heat communicated to it. But there is no such substance in nature; even lamp-black meets very imperfectly the stipulated requirements. They have of late, however, been imitated by an experimental artifice;[2] and the

[1] Day and Ostrand, *Astroph. Journal*, vol. xix. p. 40.

[2] Wien and Lummer, *Wiedemann's Annalen*, Bd. lvi. p. 453, 1895.

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facilities for investigation thus acquired prove of high value. Yet the laws of radiation securely established with their aid are, in all probability, conformed to only approximately by the sun. For the photosphere is certainly not, strictly speaking, a "black body."

Stefan's law defines the rate at which increase of radiative intensity corresponds with growing temperature. It is as the fourth power; a body rendered, for instance, twice as hot will radiate sixteen times more powerfully than before. Nor is this a purely empirical rule. Boltzmann brought thermodynamical considerations to its support in 1884, and Planck deduced it in 1900 from the electro-magnetic theory of light.[1] Still, it may break down before the solar temperature is reached. Its validity, experimentally ascertained up to near 1200°, cannot be confidently relied upon at indefinitely exalted temperatures. Such laws of nature have usually a limited field of action, and we do not know where to fix its boundaries. This element of uncertainty affects many otherwise well-grounded conclusions. Nevertheless, high temperature research has made substantial progress; and much has been done in removing the difficulties which long stood in the way of establishing a trustworthy relation between the heat received from the sun and the sun's proper heat.

But as regards the stars the case is widely different. Direct modes of procedure are here excluded. We cannot determine stellar heat-constants, and thence infer stellar temperatures. This is rendered impossible by the fundamental circumstance that the heat reaching the earth from the stars is all but insensible. The rays of the "wan, cold moon" have a thermal power more than 150,000 times greater than that of the rays of Arcturus,[2] and Arcturus is, judging by the crude standard of direct heating effects, the hottest star of our acquaintance. No wonder, then, that quantities so minute failed to be elicited with the thermopile. Sir William Huggins made persistent experiments on the subject nearly forty years ago,[3] and Dr. Stone[4] a little later.

[1] Mendenhall and Saunders, *Astroph. Journ.* vol. xiii. p. 30.
[2] Nichols, *Astroph. Journ.* vol. xiii. p. 102.
[3] *Proc. Royal Society*, vol. xvii. p. 309.
[4] *Ibid.* vol. xviii. p. 159.

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Edison tried his tasimeter in 1878, Boys his radiometer in 1888;[1] both vainly. At last, in 1895, Professor Minchin succeeded in converting stellar energy into electromotive force;[2] yet his results, though genuine, were not wholly legitimate, owing to the strong selective preferences of the sensitive cells.[3] Those, on the other hand, obtained by Professor Nichols at the Yerkes observatory in 1900 were of unequivocal significance. The beams to be examined, after being concentrated by a two-foot mirror, fell upon the vanes of a radiometer so delicately impressionable as to detect temperature-differences not exceeding one ten-millionth of a degree centigrade. Responsive deflections were, accordingly, registered, undoubtedly due to radiated stellar energy; and they varied from star to star, those caused by Arcturus being more than twice as large as those which the white rays of Vega had power to produce.[4]

The outcome is in many ways hopeful. Not that the remotest prospect can be discerned of arriving, by this straightforward route, at the absolute temperatures of the stars; but that it opens a way by which, with much further care and study, some knowledge of their relative temperatures may be gained. And even in this direction progress is seriously hampered by diversities of absorption in stellar atmospheres. We know by everyday experience that a glowing object changes from red to white as it grows hotter. So likewise with the stars. The larger the proportion of light to obscure heat in their radiations, the higher their temperatures must be. But we do not see the stars as they are in themselves. Their faces are veiled by absorptive envelopes, and far more closely veiled in some cases than in others. Moreover, the effect of absorption in the bodies strongly affected by it is to modify very materially the relation of luminosity to thermal intensity in the emissions they send out. The upper sections of the spectrum are those chiefly encroached upon; the stars are rendered fulvous, and reduced to a lower grade of photometric magnitude than should be assigned to them if their

[1] *Proc. Royal Society*, vol. xlvii, p. 480.
[2] *Ibid.* vol. lviii. p. 142.
[3] Nichols, *Astroph. Journ.* vol. xiii. p. 163.
[4] *Ibid.* p. 135.

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intrinsic brilliancy were fully displayed. Now, Arcturus is a solar star of a reddish tinge; its blue rays pay heavy toll in traversing its photospheric envelope. Not so those of Vega, which escape virtually scot-free to the open. It follows that comparisons between them are made on unfair terms. If they were equalised, Arcturus would seem much more brilliant than it does now, and the proportion of its heat to its light would be redressed. And it is the proportion only, we repeat, which is significant as regards temperature. Professor Nichols's result implies, on the face of it, that Arcturus stands at a lower heat-level than Vega, because, although its radiations contain absolutely more heat, they correspond to a less intense degree of incandescence. But no such deduction is admissible in view of the disparity of conditions. Nor is it possible to define the extent of the correction required. So far, then, the relative temperature of the two stars remains an open question.

Professor Nichols himself regards his attack upon the problem of stellar heat as little more than a reconnaissance by which it has been learned that the position is not impregnable. With more powerful means at command, he hopes to achieve its capture. By placing his radiometer at the focus of a five-foot mirror, he believes it should be possible to arrange white stars to the second, and red stars to the third magnitude, "in the order of the thermal intensity of their radiations." That fainter red than white stars must, owing to the quality of their self-absorption, be thus measurable has been sufficiently illustrated by the case of Arcturus. Just for this reason, however, no instructive comparisons can be instituted between stars with notably different atmospheric surroundings. The use of an identical platform of investigation for disparate objects can only lead to illusion. But by ranging white and red stars in separate series, and bringing solar stars into relation with the sun, much may be accomplished. There is no surer criterion of temperature than the distribution of energy in the spectrum. As it rises, the culminating point in the representative curve shifts steadily upward to shorter wave-lengths. Hence, by locating the maxima of emission from glowing bodies, their temperatures can be ascertained; and this Professor Nichols hopes to accomplish for the stars.

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It will be a matter of excessive delicacy; but, apart from instrumental difficulties, the method seems promising. Not that the essential incompatibilities of state between the different spectral classes can be abolished by its means; but varieties of white stars might be examined together, while solar stars could advantageously be assimilated to the sun. Thus, Capella gives a spectrum almost indistinguishable from the Fraunhofer spectrum save through the slight discrepancies occasioned by the differing light-quality of its spectroscopic companion. It is, however, an enormously larger and more luminous globe than our sun; and it would be of crucial importance to determine whether its vaster scale corresponds to a higher degree of heat. Again, Sir Norman Lockyer finds the ultra-violet spectrum of Rigel to be more extensive and intense than that of Sirius, and to be in turn surpassed, allowance being made for the lower magnitude of the star, by that of κ Orionis.[1] If these diversities can be securely associated with gradations of temperature, much would be made clear as regards the course of stellar development. And Professor Nichols's method of spectral energy-measurement promises, if effectively realised, to afford just the needed verification.

Speculations concerning relative star-heat have heretofore been based chiefly upon the study of specific linear absorption. But the observed indications refer immediately to the state of things prevailing in the reversing layers of the stars, and only indirectly to the condition of their photospheres. Moreover, their interpretation is, unfortunately, still a subject of debate. Indeed, it is more actively in debate than ever before; for, as the importance of reading their meaning aright has come to be more fully recognised, the pitfalls laid for their would-be decipherers have also become more evident and formidable.

It has long been known that the rays emitted by glowing gaseous substances alter with alterations in the mode of kindling them to luminosity. Thus, metals rendered incandescent in the electric arc give out conspicuously bright lines that show quite dimly when the same metals are burned in a flame; and similarly, lines subordinate in the arc develop into prominence through the excitement of the disruptive discharge in the electric spark. These progressive changes were, until

[1] *Proc. Royal Society*, Feb. 18, 1904.

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lately, ascribed by general, though not universal consent, to increasing temperature, the spark being, it was supposed, hotter than the arc, and the arc hotter than the flame. Adopting this view, Sir Norman Lockyer gave special attention to "enhanced" lines, and pointed out the remarkable circumstance of their selective display in the spectra of certain classes of stars.[1] It is undeniable that the brightest lines in the spark-spectra of the chemical elements are also highly characteristic of white, and more especially of helium stars; that arc-lines to a certain extent supersede them in solar stars; while in red stars with banded spectra, even flame-lines take a position of importance. And the assumption that from these modifications trustworthy information could be derived regarding the comparative temperatures of the stars in which they were observed, lay ready at hand, yet proved misleading. So early as 1888, Professors Liveing and Dewar were led by their experiments on the spectrum of magnesium to throw doubt on the received opinion that the electric spark is, in the literal sense, hotter than the arc.[2] Sir William and Lady Huggins demonstrated in 1897[3] that the calcium-lines, H and K, owe their preponderance in the sun not to extreme heat, but mainly to the inconceivable rarity of the emitting vapour, and they illustrated in 1903,[4] by photographs of the magnesium-spectrum, the sensitiveness of radiation to changes in the mode of electrical excitation. The spark-discharge is oscillatory; the released energy rushes with amazing velocity to and fro across the gap. But in the arc it assumes the character of a continuous flow; means of transport are available; it does not need to force a passage. That the ultimate particles of matter acted upon must respond very differently in each case is then easily understood. A final overthrow was given to the older opinion when MM. Eberhard and Hartmann of Potsdam pronounced,[5] after laborious investigations, the spark-spectrum to originate, not from thermal radiation, but from "electrical luminescence."

The word is of subversive import. Its introduction by

[1] *Proc. Royal Society*, vols. lxi. p. 441; lxv. p. 452.
[2] *Ibid.* vol. xliv. p. 241.
[3] *Ibid.* vol. lxi. p. 433; *Atlas of Stellar Spectra*, p. 91.
[4] *Astroph. Journ.* vol. xvii. p. 145.
[5] *Sitzungsberichte*, Berlin, Feb. 26, 1903.

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Wiedemann in 1894[1] to signify light without heat, or light in excess of temperature, licensed the adoption into orthodox physical science of certain new ideas which had long been gradually creeping to the front. They allow a wide latitude in the explanation of radiative and spectral phenomena. Luminescence may be evoked by chemical or electrical action; it may be superadded to ordinary light, or appear by itself; either a continuous or a discontinuous spectrum may be derived from it; nor is it necessarily correlated with absorption. Hence strict reasoning is precluded where there is reason to suspect its presence; for the laws of its production as yet evade research. We find, accordingly, that the spectral peculiarities detected in the various classes of stars, and long held to supply sure indications of their thermal rank, avow in the laboratory highly complex relations with vapour-density, with electrical "damping," with chemical processes, with luminescent action. We are then thrown back in our search for tests of stellar heat-power upon the varied intensity of blue radiation from stellar photospheres, allowing, as best we can, for the differences in absorption by which it is partially masked. One pair of stars—Capella and Vega—thus compared by Sir William and Lady Huggins[2] yielded an unlooked-for result. The solar orb seemed intrinsically the *bluer*, and was inferred to be the hotter of the two.

The temperatures of the stars are intimately related to their life-history. From the time when they first assume the photospheric vesture until, through decrepitude, they cease to shine, a constant waste of energy must be going forward in them *pari passu* with contraction. Yet, up to a certain point, recuperation, so far as sensible heat is concerned, takes the lead of dissipation. Cooling bodies, by a seeming paradox, rise in temperature until they cease to be wholly gaseous. The law of thermal ascent, enounced by Lane of Washington in 1870, applies, however, only to average temperature, while such indications as can be gathered by us refer to surface temperature. And this depends not so much upon the amount of heat stored in each globe as upon the facility with which it can be conveyed upward to the scene of action. Hence viscosity, gravity, chemical

[1] *Annalen der Physik*, Bd. liv. p. 604.
[2] *Atlas of Stellar Spectra*, p. 85.

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composition, enter into the account as items of unknown value. Nor is there any possibility of fixing *à priori* the point at which the external heat-power of a star begins to fall off. Too many conditions are involved. The main object of actual inquiries is to establish the thermal relations of the varieties of stellar spectra. Those of earliest type are non-metallic; they are marked by the absorption or emission of hydrogen, helium, oxygen, and nitrogen. Sir Norman Lockyer alleges abnormally high temperature as the cause of this unusual character. Metals, in his opinion, do not exist in such stars because intense heat keeps their primal elements asunder. They are dissociated, or perhaps have not yet begun to be associated. Nebulæ are nevertheless equally non-metallic with incipient stars, and it is difficult, if not impossible, to ascribe an enormously high temperature to volumes of matter in the last degree of attenuation. However this may be, the fact can scarcely be gainsaid that metals show more and more distinctly in stars as they advance towards maturity, and that the first signs of their presence are the lines "enhanced" in the laboratory when the spark-discharge replaces the electric arc. But, as time and condensation go on, the arc-lines gain upon their rivals, and in spectra of the solar type leave them utterly in the lurch. Finally, in banded spectra strong flame-lines emerge; while throughout the progression, as if to complicate matters still further, the great violet rays of calcium, although eminently characteristic of the oscillatory spark, reach their highest development in reddening stars. The entire series of changes, nevertheless, is beyond question orderly and consequential; and the obscurity of their origin will be in part cleared up should it be found possible to connect them with an equally consequential series of temperature-changes. Yet it must be owned that the trend of present inquiries is rather towards establishing for them relations with varying modes of electrical illumination than directly with gradations of thermal intensity in stellar photospheres or their reversing envelopes.

The hope of estimating temperature by locating maxima of intensity in discontinuous radiations is probably fallacious. Sir George Stokes, already in 1876, held it possible that the intenser blue radiation with increase of heat obvious in con-

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tinuous spectra might extend to spectra composed of separate rays—that the intensest line might shorten in wave-length as thermal energy was gained by the emitting vapour.[1] And M. Langenbach obtained, in 1903, some experimental indications of the actual subsistence of some such relation.[2] He considers, indeed, that Professor Campbell's observation of the greater strength in the Orion nebula than in vacuum-tubes of the more refrangible hydrogen-lines affords proof of a difference of temperature which may eventually be measured in thermometric degrees. Professor Keeler, too, had inferred from the singular vividness of the green and blue hydrogen emanations in all gaseous nebulæ "either a high temperature of the gases emitting the light, or a state of strong electrical excitement."[3]

The conditions of electrical excitement in heavenly bodies cannot as yet be defined. That they are present in some cases more fully than in others is, however, virtually certain; and many anomalous appearances will doubtless find an appropriate explanation when they come to be interpreted as electrical manifestations. Meantime, we can only reason about what comes more or less within the range of tangible acquaintance; and experience is wholly contradictory of the notion that nebulæ are excessively hot bodies. On the adopted principle they should be at least 3000° C. hotter than the solar chromosphere, in which red hydrogen-light is predominant, while nebular hydrogen shines exclusively, it might be said, with green, blue, and ultra-violet emissions. Further, in many variable stars the leading bright hydrogen line is the dark blue Hδ, C and F (Hα and Hβ) being equally invisible. This relation, if interpreted on the basis of Wien's law of spectral energy, would lead to the inference of fabulous temperatures as prevailing in such stars. It is, however, most improbable that Wien's law is really applicable to bright-line spectra. "The radiation from gases," we are told on high authority, "is usually wholly or partially luminescent."[4] This means that its calorific dependence is slight and secondary. Hence nothing can be

[1] *Proc. Royal Society*, vol. xxiv. p. 353.
[2] *Annalen der Physik*, No. 4, 1903.
[3] *Publ. Lick Observatory*, vol. iii. p. 228.
[4] Day and Orstrand, *Astroph. Journ.* vol. xix. p. 31.

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authentically learned from its quality regarding the temperature of its source.

The science of stellar thermotics is, in fact, still in a tentative stage. The most assured datum at its command is the temperature of the sun, which at least supplies a term of comparison for the temperatures of the stars. It is fairly certain that the effective heat of the solar photosphere, measured on the thermometric scale, is 6000° to 6500° C. And there is some probability that the sun has never been, and will never be, much hotter than it is now. But this does not imply that none of its compeers exceed it in thermal power. Those of greater mass must develop proportionately more heat, so that it is quite likely that giant suns of the solar type, such as Capella and Arcturus, radiate far more intensely per unit of area than our sun, and have photospheres hotter in the due ratio of the "fourth power" increase.

Stars with banded spectra are generally admitted to have made a further advance in cooling. Yet, despite the heavy losses in total heat incident to protracted radiation, their superficial temperatures may have suffered only a slight decline. The development of flutings in their spectra is not decisive on this point. Recent investigations tend to show that it is an index, not so much to the degree of excitement produced by heat, as to the kind of agitation set up by electricity in the originating vapour.[1] Nor have we any absolute assurance that heat-expenditure proceeds uninterruptedly. Current hypotheses on the subject possibly need revision. Regenerative agencies may, under given circumstances, be called into play. The many suggestions of "radiology" (as the new science of radio-activity might be designated) cannot be inconsiderately set aside. They are, however, too vaguely conveyed to be profitably discussed. The cosmical effects of these novel phenomena elude just yet our mental grasp. They may prove to be of stupendous importance; to the future is reserved the task of unfolding their character and scope.

[1] Trowbridge, *Amer. Journ. of Science*, vol. iii. p. 117, 1897; Hale, *Ency. Brit.* vol. xxxii. p. 779, art. Spectroscopy; Pringsheim, *Rapports du Congrès International de Physique*, t. ii. p. 108.

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CHAPTER VII

TEMPORARY STARS

THE facts connected with the light-changes of stars are in the highest degree strange and surprising; and wonder does not lessen as familiarity with them grows. They are of everyday occurrence; they can be predicted beforehand, in many cases with nearly as close accuracy as an eclipse of the sun or moon, and they affect in manifold ways a great number of objects. Stellar variability is of every kind and degree. With the regularity of clockwork some stars lose and regain a fixed proportion of their light; others show fitful accessions of luminosity succeeded by equally fitful relapses into obscurity; many waver, in appearance lawlessly, about a datum-level of lustre itself perhaps slowly rising or sinking. The rule of change of a great number is that of an evident, though strongly disturbed periodicity; a few seem to spend all their powers of shining in one amazing outburst, after which they return to their pristine invisibility or insignificance.

The amount is as much diversified as the manner of fluctuation. Changes of brightness so minute as almost to defy detection are linked on by a succession of graduated examples to conflagrations in which emissive intensity is multiplied a thousand times or more in a few hours. The range of variation is in some stars sensibly uniform; they subside during each crisis of change to the same precise point of dimness, and recover without subtraction or excess, just so much light as they had before. In others it is widely irregular. The limits of fluctuation in one period furnish no

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precedent to be conformed to in the next. Nothing is predetermined; the intensity of each phase seems to depend upon a complex set of conditions unlikely to recur twice in the same precise combination.

The first effort to regularise the phenomena of variable stars was made by Professor E. C. Pickering in 1880.[1] His five classes, though often enough (as might be expected) confused at the borders, are still sufficiently distinct to form a useful framework for the facts. They are as follows: Class I. includes temporary or "new" stars; Class II., stars like "Mira" Ceti, strikingly variable in periods of several months; Class III., stars subject to irregular fluctuations; Class IV., variables with periods of a few days exemplified by δ Cephei and β Lyræ; Class V., "Algol-variables," or stars like Algol in Perseus undergoing brief obscurations at fixed intervals. We will take each in turn, beginning with the first.

A temporary star may be defined as a variable attaining one single, vivid maximum. A swift rise to such a height as to constitute a virtually "new" object, followed by a slower yet prompt decline, characterise these outbursts, close upon thirty of which have been more or less credibly recorded within historical times. The genuineness of those stated to have occurred in the following years[2] is, in only a very few cases, open to cavil.

134 B.C. in Scorpio; the star of Hipparchus.

123 A.D. in Ophiuchus.

Dec. 10, 173, between α and β Centauri. Conspicuous; scintillated strongly; visible eight months.

386 (April to July) between λ and ϕ Sagittarii.

389, near α Aquilæ, said by Cuspinianus to have equalled Venus; vanished after three weeks.

March 393, in the Tail of the Scorpion.

827 (?) in Scorpio. Observed during four months at Babylon. There is some uncertainty about the date, none about the fact.

May to August 1006, in Scorpio.[3] Described by Epidamnus, the monk of St. Gall, as "oculos verberans."

[1] *Proceedings Amer. Acad.* vol. xvi. p. 17.
[2] See Humboldt's *Cosmos*. vol. iii. p. 209 (Otté's translation).
[3] Schönfeld, *Astr. Nach.* No. 3034.

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July 1203, in the Tail of the Scorpion; said to have resembled Saturn.

1230, in Ophiuchus.

1572, Tycho's star in Cassiopeia.

1604, Kepler's star in Ophiuchus.

1670, in Vulpecula.

1848, in Ophiuchus.

1860, in Scorpio.

1866, in Corona Borealis.

1876, in Cygnus.

1885, in Andromeda.

1887, in Perseus; discovered by photography.

1891, in Auriga.

1893, in Norma;
1895, in Carina;
1895, in Centaurus;
1898, in Sagittarius;
1899, in Aquila;
} all photographic detections.

1901, in Perseus.

1903, in Gemini; found on the Oxford chart-plates. Making a total of twenty-seven, besides four or five questionable instances mentioned in Chinese annals.

The most noteworthy feature of this list is the curiously partial distribution of the objects enumerated in it. All but one of them lie in the thoroughfare of the Milky Way, and nine are clustered together in the section of it marked by the stars of the Scorpion and the Serpent-tamer. In time also the grouping of the apparitions is strikingly unequal. The occurrence of three within the seven years 386 to 393 A.D. was succeeded by a blank of four and a half centuries. Kepler's came pretty close upon Tycho's star; none were recorded between 1670 and 1848; then, within little more than half a century, seven "Novæ" attracted visual attention, and six made their marks upon sensitive plates.

The brightest sidereal object known to us by authentic description was the "stranger-star" in Cassiopeia, observed by Tycho Brahe.[1] He first saw it November 11, 1572, but it

[1] Wolf, *Geschichte der Astronomie*, p. 414; Kaiser, *De Sterrenhemel*, Part i. p. 582; Lynn, *Observatory*, vol. xvi. p. 268; Dreyer, *ibid.*, vol. xxiv. p. 166.

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had already been noticed by Wolfgang Schuler at Wittenberg, November 6, and by Lindauer at Winterthür, November 7, while Maurolycus entered upon its systematic study at Messina, November 8. Observed by Tycho to be the rival of Venus, it showed to keen eyes at midday, and at night through clouds thick enough to obscure every other star. After about three weeks, however, it began to fade, and in March 1574 disappeared finally. Its colour was at first dazzlingly white, then for a while ruddy, and from May 1573 onward, pale with a livid cast. Rapid scintillation distinguished it throughout.[1] There is no reason to suppose the outburst other than solitary. The appearances in the years 945 and 1264 connected with it by a Bohemian astrologer named Cyprian Leowitz[2] were almost certainly apocryphal.[3]

The "new" star (designated "B Cassiopeiæ") can still be perceived smouldering in the spot where it once blazed. Tycho's measurements, reduced and discussed by Argelander, located it within one minute of arc of a reddish, eleventh magnitude star, the character of which, as disclosed by the observations of Hind and Plummer in 1870-4, and of Safarik, 1888-90,[4] fully warrants the inference of its identity with the famous "temporary." Not only is it variable to the extent of nearly a magnitude, but it frequently seems hazy and ill-defined, as if through some abnormality in the quality of its light.

The star of 1604 ran a parallel course to that of 1572. Discovered by Maestlin, October 9, and observed by Galileo at Padua, October 10, it quickly overtopped Jupiter, but by the end of March 1605 had sunk to the third magnitude, and a year later vanished. Kepler describes it as "sparkling like a diamond with prismatic tints,"[5] but says nothing of progressive changes of colour. "Nova Serpentarii," has left behind no clearly identifiable representative.

The next "new star" was discovered near β Cygni on June

[1] Tycho, *De Novâ Stellâ anni* 1572, p. 302.

[2] Tycho, *Judicium de Novâ Stellâ.*

[3] Lynn, *Observatory*, vol. vi. pp. 126, 151; Sadler, *English Mechanic*, vol. xxx. p. 402; Tycho Brahe, *Progymnasmata*, p. 331.

[4] *Monthly Notices*, vol. xxxiv. p. 168; Gore's *Catalogue of known Variables*, p. 164; *Astr. Nach.* No. 2950.

[5] Kepleri *Opera*, t. ii. p. 620.

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20, 1670, by Anthelmus, a Carthusian monk at Dijon. It was then of the third magnitude, but its decline, unlike that of others of its class, was interrupted by two reappearances separated by intervals of invisibility. Between March and May 1671, it rose from the fourth to the third rank, then died out, only flickering up to the sixth magnitude in March 1672.[1] Almost exactly in its assigned position, Mr. Hind picked up, April 24, 1852, a star between the tenth and eleventh magnitude, which, when reobserved in 1861, had lost more than half its light, and gave the blurred image characteristic of many superannuated Novæ.[2] The triple maximum of Anthelm's star assimilates it to Janson's variable P Cygni,[3] which has itself often been classed as a Nova.

An object unequivocally such was detected by Mr. Hind in Ophiuchus, April 28, 1848, when it was of 6·7 magnitude, and intensely reddish yellow.[4] Four days later it had mounted above the fifth magnitude, from which eminence it slowly descended, making no lasting halt until, in 1874-5, it had got down to the thirteenth magnitude.[5]

With the spectroscopic study of temporary stars, a fresh chapter in our knowledge of them opened. Through the magic of the prism, more was ascertained as to their essential nature in five minutes than could have been learned in as many centuries with the telescope alone. On May 12, 1866, Mr. John Birmingham, of Millbrook, near Tuam in Ireland, was amazed to perceive an unfamiliar star of the second magnitude shining in the constellation of the Northern Crown. On May 16, the application of Sir William Huggins's spectroscope showed the object to be wrapped in a mantle of blazing hydrogen. Five bright lines (three of them due to hydrogen) stood out from a range of continuous light broken up into zones by flutings of strong absorption.[6] The incandescence of the star was hence largely atmospheric, and for the rest, from the rapid rate at which it fell away, could have been only

[1] J. Cassini, *Éléments d'Astronomie*, p. 69.

[2] *Monthly Notices*, vol. xxi. p. 231; *Nature*, vol. xxxii. p. 355. The star is No. 1814 in the Greenwich Catalogue for 1872.

[3] See *ante*, p. 62.

[4] *Astr. Nach.* Nos. 636, 638, 672.

[5] *Monthly Notices*, vol. xxi. p. 232.

[6] *Proceedings Royal Society*, vol. xv. p. 146.

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"skin-deep." Although the light decreased by a daily half magnitude, and its colour changed from white to orange, no alteration took place in the character of the spectrum. The bright rays, however, faded somewhat less quickly than their continuous background.

The visibility of the object to the naked eye lasted only eight days, and already, in the beginning of June, it had sunk to the ninth magnitude. Its slow subsequent decline was interrupted by fluctuations, thought by Schmidt to be periodical in about ninety-four days.[1] When observed by Vogel, March 28, 1878, and again by Barnard in 1902, it was of about 9·5 magnitude, and gave an ordinary stellar spectrum.[2] Virtually, it had resumed the conditions of its existence when Schönfeld entered it as of 9·5 magnitude in the Bonn Durchmusterung. Its leap upward to the second magnitude, involving a *thousand-fold* gain of light, was accomplished with extraordinary suddenness. Two hours and a half previously to Birmingham's discovery, Schmidt surveyed at Athens the constellation in which the blaze was about to occur, and noticed nothing unusual. He was certain that the star could not then have been as bright as the fifth magnitude.

Although its character as a Nova seems undoubted, the name of "T Coronæ" was bestowed upon it in conformity with Argelander's system of nomenclature, by which the variables in each constellation are designated, in the order of their discovery, by the Roman capital letters from R onward. Only stars otherwise anonymous, however, are included in the distinctive series thus created, so that many variables are still entitled in the ordinary way by Greek letters.

The stellar apparition that ensued after ten years was, in some of its features, the most remarkable of all. Dr. Schmidt noticed at Athens, November 24, 1876, a star of the third magnitude near ρ Cygni, in a spot till then untenanted by any known stellar inmate. The weather having been cloudy during the previous four days, there was no possibility of tracing the steps of its ascent, but it ran down very rapidly, and ceased to be visible to the naked eye on December 15.

[1] *Astr. Nach.* No. 2118.

[2] *Monatsberichte*, Berlin, 1878, p. 304; *Monthly Notices*, vol. lxii. p. 418.

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Its changes of colour pursued an inverse order to those of its predecessor. From golden yellow it turned white, and eventually bluish.

The earliest spectroscopic examination of "Nova Cygni" was made by M. Cornu at Paris, December 2 and 4.[1] Just the same range of bright lines was measured by him which would start into view in the solar spectrum upon a considerable augmentation of incandescence in the sun's gaseous surroundings. Besides three, if not four, hydrogen lines, there were the yellow helium ray (wave length 5875), with several of its subsequently identified companions, the magnesium group *b*, and probably the sodium D. The star, at the height of its outburst, scarcely seemed to diverge from the type of β Lyræ and γ Cassiopeiæ. The C of hydrogen was vivid; the continuous spectrum strong. But as the light diminished remarkable changes supervened.[2] Red hydrogen insensibly yielded its supremacy to green; only a faded remnant of the general prismatic radiance survived in the yellow and blue; helium ceased to glow; and the lazulite band of γ Velorum (nitrogen?), identified by Copeland, January 2,[3] gained unexpected prominence.

Meanwhile, the chief nebula-line, usurping the place, as it were, of an adjacent green line of helium, had been steadily creeping to the front; and when observations, suspended in March owing to the encroachments of daylight, were resumed by Dr. Copeland at Dunecht, September 2, 1877, it stood alone.[4] All the surviving light of the object—by that time sunk to 10·5 magnitude—was concentrated in that solitary green ray, and a minute planetary nebula was, in appearance, substituted for a star. But this too proved to be a phase scarcely less transient than the rest. Three years later, when the Nova had dropped a couple of magnitudes lower still, indications were obtained at Harvard College of its affording an ordinary stellar spectrum.[5] They were fully confirmed from the evidence of a spectrogram taken by Mr. Palmer, with the Crossley reflector, August 12, 1901, which showed

[1] *Comptes Rendus*, t. lxxxiii. p. 1172.
[2] Lockyer, *Proc. Royal Society*, vol. xliii. p. 139.
[3] *Copernicus*, vol. ii. pp. 102, 112.
[4] *Ibid.* p. 106.
[5] *Annual Report*, 1879-80, p. 7.

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the faint rays of Nova Cygni to be unmistakably continuous. Professor Barnard observed them shortly afterwards with the Yerkes 40-inch refractor to be visually ill-defined and bluish, the star being estimated at about 15·5 magnitude.[2] He could detect no change in its position relative to the surrounding stars mapped twenty-four years earlier by Copeland and Lohse.

The Novæ of 1866 and 1876 appear to have been of essentially the same character, notwithstanding some variety in the phenomena attending their decay. But they were not more closely assimilated by the analogous peculiarities of their light than the pair we are now about to describe by the singular circumstances of their situation. On May 18, 1860, a nebula in Scorpio, numbered 80 on Messier's list (6093 in Dreyer's New General Catalogue) was observed by Dr. Auwers at Berlin.[3] It presented its usual appearance of a somewhat hazy ball of light, brightening gradually inward, and resolvable with difficulty into separate stellar points, together constituting a closely-packed, and most likely excessively remote globular cluster. Three nights later he looked again, and saw that these minnows had a triton in their midst. A seventh magnitude star shone close to the centre of the stellar group. The existence of the new-comer lasted visibly just three weeks. Before May 25, a decline set in; it had made considerable progress when, on May 28, Mr. Pogson (uninformed of Auwers's discovery) was startled by the apparent substitution of a star for the nebula,[4] the dim luminosity of which seemed actually obliterated by the keen stellar radiance emanating from within it. It recovered, however, very speedily from this merely optical effacement. On June 10 its normal aspect was almost restored, and has never since been disturbed.

After the lapse of a quarter of a century the significance of the event was accentuated by its repetition. This time the great nebula in the girdle of Andromeda was the scene of the outbreak. The unlooked-for addition to it of a "star-like

[1] *Lick Bulletin*, No. 34; *Astroph. Journ.* vol. xviii. pp. 232, 233.

[2] *Monthly Notices*, vol. lxii. p. 405; cf. J. G. Lohse, *ibid.* vol. xlvii. p. 494.

[3] *Astr. Nach.* No. 1267.

[4] *Monthly Notices*, vol. xxi. p. 32.

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nucleus" was announced by Dr. Hartwig at Dorpat, August 31, 1885; but it turned out that the change had already been perceived by Mr. Isaac W. Ward of Belfast, August 19, and two nights earlier at Rouen by M. Ludovic Gully, who set it down as an effect of bad definition.[1] Concordant observations by Tempel at Florence, Max Wolf at Heidelberg, and Engelmann at Leipzig showed decisively that the strange object made no show down to 10 P.M. on August 16;[2] and a photograph taken by the late Dr. Common in August 1884 gave positive assurance that a year earlier its place had no stellar occupant as bright as the fifteenth magnitude.[3] What were virtually the first rays of the Nova reached the earth August 17, 1885.

Between that date and August 31 it mounted from the ninth to the seventh magnitude; then without delay entered upon nearly as swift a downward course, checked by only one decided pause. Even the largest telescopes failed to keep it in view after March 1886. The full yellow colour, by which the star at first contrasted effectively with the silvery background it was projected upon, faded with its light. No haze or glow blurred its image, which remained sharply stellar with a power of 1100 on the great Princeton refractor, when the adjacent nucleus of the nebula melted into a confused luminous blot.[4] Attempts, incomplete from the nature of the case, made by Dr. Franz at Königsberg, and by Professor Hall at Washington, to determine the parallax of Nova Andromedæ, gave only negative results.[5] So far as they were significant at all, they indicated its immeasurable remoteness from the earth, nor should it be overlooked that Sir Robert Ball's similar experiment upon Nova Cygni had intimated a similar conclusion.[6]

The spectrum of Nova Andromedæ was of a dubious character. It bore witness to a completely different order of incandescence from that of the "blaze-stars" in the Northern Crown and the Swan. The bright rays which it perhaps included were inconspicuous. None were definitely determined,

[1] *Ciel et Terre*, Oct. 1, 1885.
[2] *Astr. Nach.* Nos. 2682, 2688, 2691.
[3] *Nature*, vol. xxxii. p. 522.
[4] Young, *Sidereal Messenger*, vol. iv. p. 282.
[5] *Astr. Nach.* 2816.
[6] *Dunsink Observations*, Part V. p. 24.

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though the presence of several in the green and yellow[1] was strongly suggested to Sir William Huggins on September 9; and Dr. Copeland succeeded, on September 30, in getting rough measures of three vaguely discernible accessions of brightness.[2] The light, however, was mainly continuous; and a general resemblance in quality of radiance was one of many arguments proving a physical relationship between the star and the nebula. This was, indeed, superfluously evident. That *one* stellar conflagration should by chance be projected almost accurately upon the core of a nebula in reality disconnected from it, is just conceivable; that *two* such highly improbable events should occur within twenty-five years of each other distances possibility. A third was barely rescued by photographic agency from irrevocable oblivion.[3] Discovered by Mrs. Fleming when its course was already nearly run, enough was nevertheless learned about Nova Centauri to place beyond doubt its analogy with its two predecessors. The nebula, in an outlying part of which it was lodged, is catalogued as N.G.C. 5253; the spectrum of the star, fortunately recorded by a casual exposure in July 1895, showed the same irregularly continuous character with that of Nova Andromedæ. We may then feel assured that the Novæ of 1860 and 1885, as well as that of 1895, were situated within the substance of the several nebulæ which they temporarily illuminated.

This collocation obviously falls into line with the galactic affinities of other temporary stars. The Milky Way is a plane of condensation for all small stars, but more especially, and in a marked degree, for stars as well as nebulæ of a gaseous nature. Temporary stars are closely cognate with these, not merely through the brief gaseous incandescence bringing them to our notice, but through the symptoms of nebulosity which survive it. Opportunities for their study have lately been numerous and varied. Dr. Anderson of Edinburgh is distinguished as the visual discoverer of the two most remarkable Novæ that have appeared for some centuries. He announced the addition of a guest to the stellar family of the Charioteer, February 1, 1892; but the Harvard photographs were found

[1] *Report Brit. Association*, 1885, p. 935.
[2] *Monthly Notices*, vol. xlvii. p. 54.
[3] *Fifty-first Harvard Report*, p. 7.

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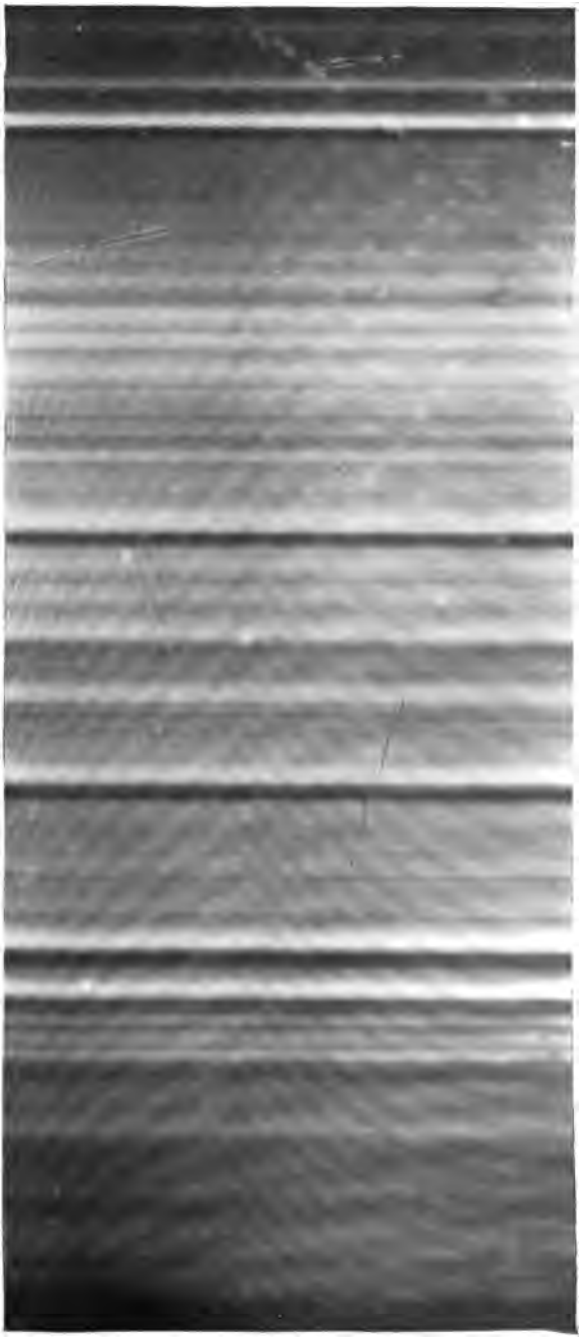
PLATE VI.



Spectrogram of Nova Aurigæ (Pickering).

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to have silently noted the event on December 10, 1891, and the star's maximum brightness was fixed from their evidence at 4·4 magnitude on December 20. Spectrographic methods, applied for the first time to such an outburst, disclosed some profoundly significant peculiarities, since ascertained to be generally characteristic of "temporary" star-light. They consist mainly in the great width of the spectral lines, in the duplication of the bright by a corresponding dark series, and in their large relative displacements. A fine spectrogram of Nova Aurigæ, taken at Harvard College during an early stage of its development, is reproduced in Plate VI. Three brilliant hydrogen-lines, beginning with F on the right, are visible in it with their obscure, more refrangible companions; the H and K of calcium are similarly conspicuous to the left; while the hydrogen-series is continued in a less pronounced manner beyond them in the ultra-violet. It is instructive to compare with it (see Plate VII.) a map of the same spectrum, drawn by Father Sidgreaves from two photographs taken at Stonyhurst, February 3, 1892. It is in two sections. The upper contains all the lines apparently present, the lower those that were evident and indubitable. The shorter wave-lengths, it will be noticed are here on the right hand; F is in the middle, and D, undivided and distended, is placed near the extreme left. The hypothesis of a double origin for this extraordinary spectrum irresistibly suggested itself. Two stars, one shining with vivid gaseous emissions, the other showing heavy absorption-lines, were supposed to be in the act of rushing past each other with enormous opposite velocities, a grazing collision, or tidal influence being invoked to account for the conflagration by which they were rendered suddenly conspicuous. Accumulated incongruities, however, have thrown discredit upon the "two-star" theory, and it has now few adherents. That an encounter so wonderfully circumstanced should occur just once was conceivable; but the repetition of virtually identical occurrences year after year transcended the powers of reasonable assent.

Nova Aurigæ followed the example of a nebular transformation set by Nova Cygni, the change being in its case accompanied by a very considerable recovery of lustre. The star, then of sixteenth magnitude, was lost sight of in April 1892; in August, its light, multiplied some three

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hundred times, was mostly collected into the green ray of nebulium (λ 5007). Nor did it begin to ebb away again for many months, and then only at the slow rate of about half a magnitude yearly. Mr. C. D. Perrine observed it in August 1903 to be of the fourteenth magnitude; and actually succeeded in obtaining a legible spectrographic impression of its faint rays. They proved to have nearly lost their gaseous character; the continuous streak yielded by them included only bare traces of bright lines.[1] The rule, in fact, seems general for temporary stars of reversion to a stellar type after a more or less prolonged nebulous interlude.

Four new stars, discovered photographically by Mrs. Fleming,—Nova Normæ in 1893, Nova Carinæ in 1895, Nova Sagittarii in 1898, and Nova Aquilæ in 1900,—followed closely in the track of Nova Aurigæ. They deviated very little from the pattern of its spectrum,[2] and they underwent similar metamorphoses, only vanishing more quickly and more completely. They were then essentially phenomena of the same order, though probably on a reduced scale, since the duration of a Nova's phases may serve as a rough measure of its real magnitude. Clearly outbursts of the kind are incidents that occur with method, and call for an explanation capable of being uniformly applied.

The difficulty of finding one comprehensive enough for the purpose was not lessened by the strange disclosures connected with the apparition of Nova Persei. Early in the morning of February 22, 1901, Dr. Anderson saw with astonishment that Algol had a twin-companion, which, thirty hours later, was super-eminent in the northern sky. It was not until February 24 that its light was distinctively that of a Nova; but the seeming delay may have been due to its prompt discovery. None of its predecessors had been caught on the rise and at once spectroscopically examined. If they had, it would probably have been found that the gaseous blaze invariably needs some time to develop. It took place in Nova Persei precisely in the same way as in Nova Aurigæ

[1] *Lick Bulletin*, No. 48; cf. Palmer, *ibid.* No. 35; Barnard, *Monthly Notices*, vol. lxii. p. 418.

[2] That of Nova Sagittarii showed no conspicuous dark lines when photographed April 19, 1898; but this was a comparatively late record; it is amply possible that the usual chiaroscuro effects had been apparent a month previously.

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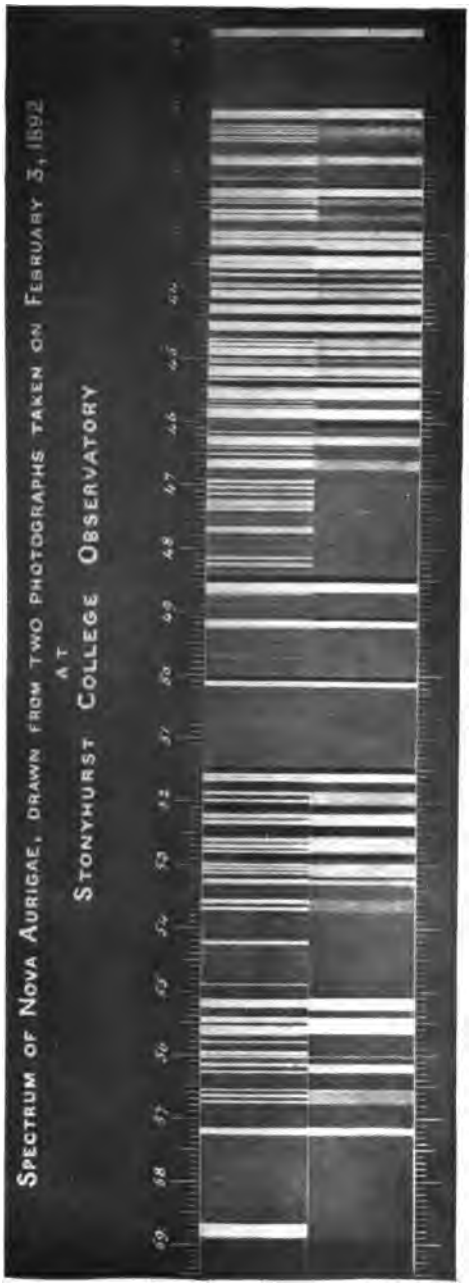

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and its less noted imitators. That is to say, the bright bands were shadowed on their blue sides by heavy bars of absorption; and these were shifted from their normal places by amounts corresponding, on Doppler's principle, to the well-nigh incredible approaching velocity of one thousand miles a second!

The decline of the star was interrupted and irresolute. During March, indeed, the interruptions amounted to vivid spasms of recovery periodical in three days. Yet the loss of light progressed despite of them. By September 1901 the once brilliant Nova had ceased to be visible to the naked eye.[1] The singular nature of the corresponding spectrum can be gathered from an inspection of Plate VIII., Fig. 1, in which, by the kind permission of Father Sidgreaves, two of the Stonyhurst photographs are reproduced. The differences between them, it should be noted, are mainly of instrumental origin; so that the sum of what each records gives a fair picture of the emission-rays of Nova Persei after it had dropped below the sixth magnitude. It had descended to the tenth in October 1902; and its colour throughout that year was dull white or bluish,[2] whereas it had at first been strongly red. A spectrogram taken by Mr. Perrine, July 30, 1903, when it was of about the twelfth magnitude, indicated that the nebular rays for some time predominant had lost strength concomitantly with the usual restoration of continuous light;[3] and we may be sure that the equalisation will progress until every spectral trace of the strange cataclysm of February 1901 has become effaced.

One of its accompaniments or consequences was absolutely without precedent. A circumferential nebula was partially photographed by Dr. Max Wolf, August 23, 1901;[4] and it came out as a complete series of spires issuing, it might be said, from the Nova as their origin, in a Yerkes photograph of September 20. Later impressions, secured at the two great American observatories, supplied evidence, the startling purport of which was independently perceived by Mr. Perrine[5] and

[1] Jost, *Astr. Nach.* No. 3821.

[2] Barnard, *Monthly Notices*, vol. lxii. p. 418; Rambaut and Williams, *ibid*, June 1902.

[3] *Lick Bulletin*, No. 48.

[4] *Astr. Nach.* Nos. 3736, 3752, 3753.

[5] *Lick Bulletin*, No. 10.

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Mr. Ritchey, that the nebula was expanding at a portentous rate, its swathed folds spreading outward, month by month, like the ripples on a water-surface disturbed by the fall of a stone. Moreover, this had been going on steadily from the initial date of the star's visibility. A Crossley-reflector plate was found to have been impressed in ten minutes, March 29, 1901, with narrow nebulous coils, the obvious progenitors of those fully disclosed six months later. For they were narrower in the computed proportion of the time elapsed, and would, at the same rate of expansion, have started from their focus in the star a few days before its observed outbreak. In Plate IX. the Lick photographs of March and November are shown in juxtaposition. The augmented spread of the nebulosity during the interval can be gauged by using the small star to the north-west of the Nova as a point for comparison. In the earlier picture it lies far out in the clear sky, like a rock near high-water mark at low tide; in the second, it is heavily involved in folds of cosmic cloud.

Theories of the expanding nebula round Nova Persei had to meet arduous conditions. The star has no appreciable parallax; and the indefinite remoteness thus implied for it gave almost an assurance that the speed of the observed movements in its neighbourhood could not have been inferior to that of light transmission. Hence the idea occurred simultaneously to Professors Kapteyn and Seeliger, and to Mr. W. E. Wilson, that the motion concerned was ethereal, not material.[1] What we saw resulted, they thought, from the progressive illumination by the sudden stellar blaze of a pre-existent dark formation. The rays photographed were those of the Nova reflected from nebulous particles multitudinously strewn round its place. The supposition, indeed, of a dark star lurking in the midst of a series of spherical shells of obscure filmy material[2] is not one that invites ready assent; nor did the observed movements within the nebula fit in quite satisfactorily with the illumination-hypothesis. It had to encounter, besides, the difficulty that the light proceeding

[1] *Astr. Nach.* Nos. 3756, 3759; *Nature*, vol. lxv. pp. 198, 298.

[2] The effect, viewed from the earth, would have been that of a paraboloidal surface projected on a plane. See the demonstration by O. Luyties, *Astroph. Journ.* vol. xix. p. 131.

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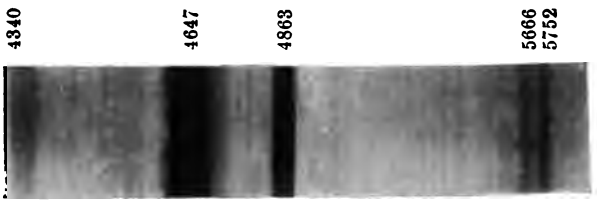
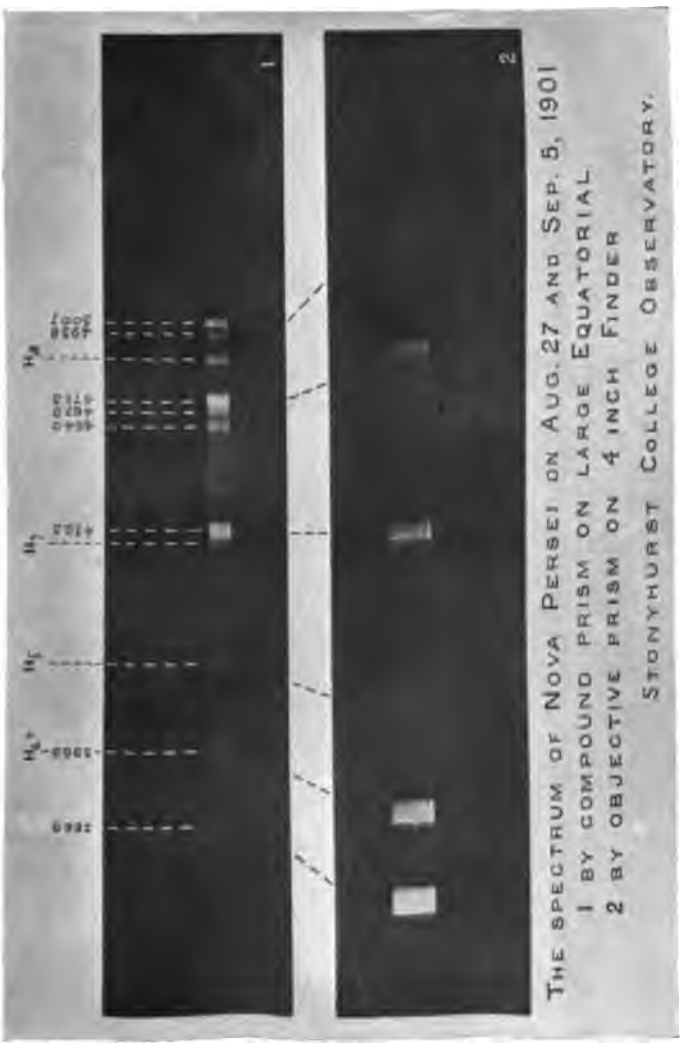


Spectrogram of Nova Geminorum, March 28, 1903 (Frost).


THE SPECTRUM OF NOVA PERSEI ON AUG. 27 AND SEP. 5, 1901
1 BY COMPOUND PRISM ON LARGE EQUATORIAL.
2 BY OBJECTIVE PRISM ON 4 INCH FINDER
STONYHURST COLLEGE OBSERVATORY.
1
2

Spectra of Temporary Stars.

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from the nebula was not polarised, as it should have been if reflected; and Professor Newcomb considered that the distance of the nebulous spires from the Nova must have been so great as to preclude the possibility of their shining perceptibly by means of its enfeebled light.[1] Thus the weight of opinion ultimately favoured Professor Very's hypothesis[2] that the nebulous structure connected with Nova Persei resulted from its actual emission of minute particles under the stress of electrical repulsion, or the subtle agency of light-pressure.

Nova Geminorum was discovered by Professor Turner as an intruded star of the seventh magnitude on a plate taken at Oxford, March 16, 1903. The Harvard College photographic archives were then consulted, and a record of the star's maximum on March 6, at 5·0 magnitude, was extracted from them; while a negative of March 1, showing stars down nearly to the twelfth magnitude, preserved no trace of it. Mr. Newall found its spectrum, on March 26, to be ablaze with hydrogen and helium; and a photograph of so much of it as could be brought into focus at one exposure with the Yerkes refractor, obtained by Professor Frost, March 28, is reproduced in Plate VIII., Fig. 2. Its predominant feature is the strong effulgence of the Wolf-Rayet lazulite band; the green hydrogen ray to the right is of only half its width; the faintness of Hγ (blue hydrogen) is partly due to its unfavourable situation; but Hα was perceived visually to be of great intensity, and lent to the star its characteristic crimson tint.[3] Colour and brightness faded together, and very rapidly, the transience of the conflagration suggesting that it affected a comparatively small mass. The decadent Nova was observed by Professor Barnard, September 1, 1903, as a hazy star of 11·5 magnitude,[4] yielding, it had been ascertained at Lick, August 17, a purely nebular spectrum;[5] and it will doubtless sink ere long to virtual extinction.

The manifold experience of recent years has taught us

[1] *Astr. Journ.* No. 550.

[2] *Astr. Nach.* No. 3771; *Amer. Journal of Science*, vol. xvi. p. 49.

[3] *Yerkes Bulletin*, No. 19; *Astroph. Journ.* vol. xvii. p. 376.

[4] Turner, *Monthly Notices*, vol. lxiii. p. 565.

[5] H. D. Curtis, *Lick Bulletin*, No. 48; *Publications Astr. Pacific Society*, Oct. 1903.

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that a representative "temporary" spectrum passes through five well-marked stages. To begin with, it seems—though for a very brief interval—that of an ordinary helium-star. Next, it displays a series of brilliant rays, set off by dark satellites, always of shorter wave-lengths. Later, blue bands emerge, and the light partakes markedly of the Wolf-Rayet peculiarities. Fourthly, it becomes concentrated into the green rays of nebulium. Finally, it reverts to whiteness, and disperses into a dim, featureless prismatic band. A strictly methodical course of change is then traversed by these bodies. They undergo transformations of a prescribed kind in a settled order. Nor are any of their phases necessarily and essentially unstable, since each is exhibited permanently by the members of other sidereal families. The conditions to which Novæ are temporarily subjected cannot, then, be adequately explained without reference to the fact that they are durable elsewhere. They cannot depend for their production upon the fleeting effects of catastrophes. This consideration seems to dispose of collision and explosion theories of stellar outbursts. For the displaced and coupled lines accompanying their vivid phases, which such theories are specially designed to account for, do not exclusively distinguish "new" stars. They occur as well in the spectra of permanent though peculiar denizens of the sky. The most familiar examples are P Cygni and η Carinæ. Both these stars now shine steadily, though both underwent striking vicissitudes in the past; and both show spectra perfectly similar to those of Novæ near their maxima. Their remarkable quality of light accordingly corresponds to a state of things capable of persisting year after year, decade after decade. The causes which produce it must act uniformly and for an indefinite length of time. They are not brought into action casually through some momentary combination. Now this inference obviously applies likewise to Novæ. The spectral phenomena shown by them are, it is true, of a transient nature. Yet they are the same observed to be constant in other stars. No rationale, accordingly, which expounds them on the exclusive basis of a passing catastrophe can be true.

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South.

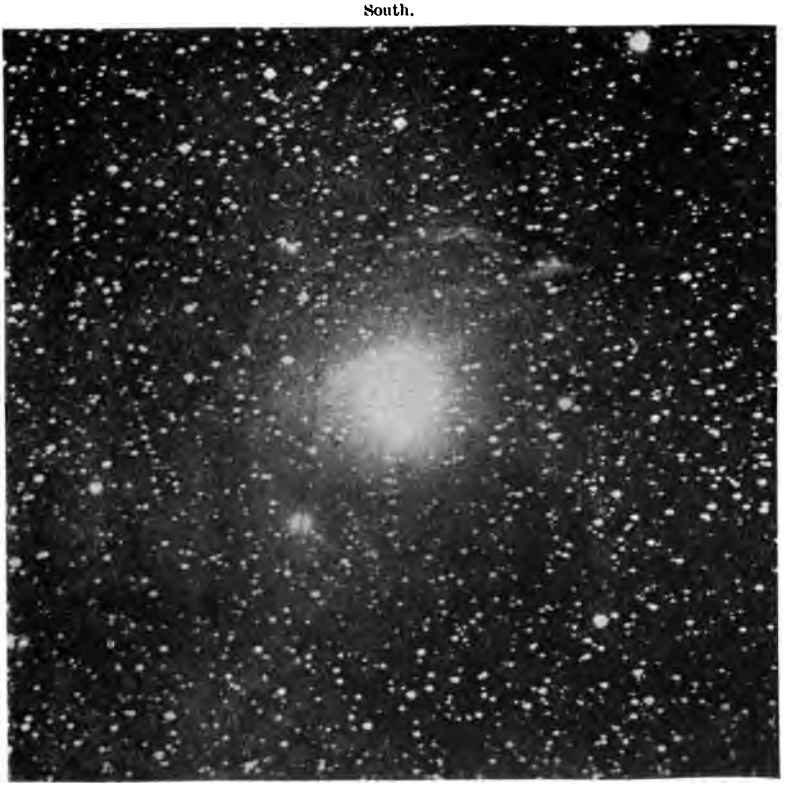
1. West.

East.

North.

South.

2. West.



East.

North.

The Nebulosity round Nova Persei.

1. In March. 2. In November, 1901.

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CHAPTER VIII

STARS VARIABLE IN LONG PERIODS AND IRREGULARLY

BETWEEN two and three thousand stars are certainly or very probably variable, and known objects of the kind multiply with the more systematic use of photographic methods. In Chandler's Third Catalogue (1896),[1] 393 were enumerated; seven years later, 1309 figured in the Harvard Provisional Catalogue[2] with its First Supplement.[3] In 1904, no less than 407 new variables were brought to light by Miss Leavitt's comparisons of Harvard plates taken at different epochs; and detections go on apace, both at Harvard[4] and at Heidelberg.[5] So far, only a small proportion (417) of the stars recognised as variable have had periods assigned to them; with most acquaintance has been made too recently for the purpose; yet a large residue seem entirely lawless in light change. Periodical stars are divided into those with "long" and those with "short" periods. Nor is the distinction an arbitrary one. The stars seem to separate of themselves into two principal groups, undergoing fluctuations in cycles of respectively less than thirty, and of 120 to 450 days. The paucity of stars with periods of intermediate lengths is shown graphically in Fig. 2, where the height of the curve represents the number of stars subject to changes proportionate in duration to the horizontal distance from left to right.

Variations requiring several months for their completion

[1] *Astr. Journal*, No. 379.
[2] *Harvard Annals*, vol. xlviii. p. 91.
[3] *Harvard Circular*, No. 77.
[4] *Ibid.* No. 96.
[5] M. Wolf, *Astr. Nach.* No. 4005.

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differ both in degree and kind from those run through in a few days. They are of much greater amplitude, ranging over five to eight instead of, at the most, two magnitudes; they are accomplished with less punctuality; and they are frequently attended by symptoms of gaseous ignition almost wholly foreign to quicker vicissitudes. Most important of all, they affect bodies of peculiar constitution. Nearly all long-period variables are red stars with banded spectra; those of short period are white or yellowish in colour, and display Sirian or solar spectra. Quality of light is thus the pre-

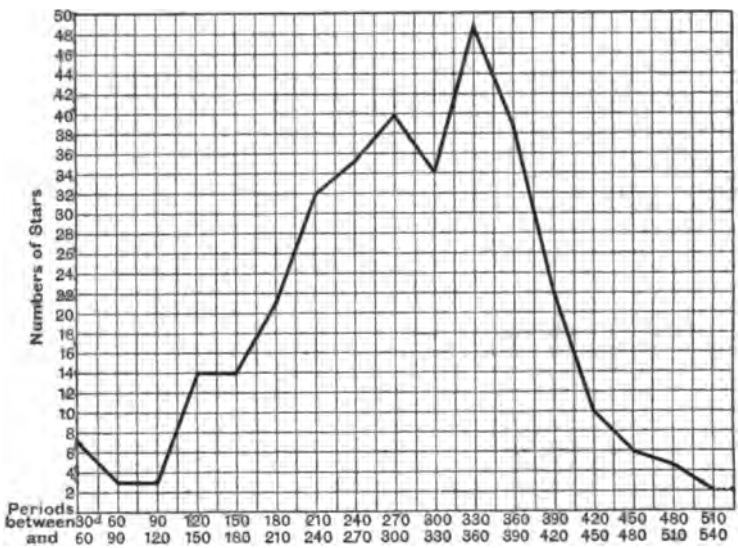

FIG. 2.—Distribution of 834 Periods of Variable Stars.

dominant factor in determining the law of stellar light-changes, and is itself dependent, as we have seen, upon atmospheric properties. The rule is, in fact, almost unfailing that short periods are attended by slight, long periods by strong absorption, and that the conditions producing redness in stars not only favour variability in general, but almost absolutely prescribe its type.

Periods of between one and two hundred days may be called "long"; but as Fig. 2 shows, they are not of plentiful occurrence. Such fluctuations as now engage our attention usually demand more than 200 days for their accomplish-

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ment, and are seldom prolonged beyond 450. Dr. Chandler considers 320 days as the average duration of change for long-period variables;[1] the prevalence, however, among them of periods of about one year is remarkable, and cannot be accounted for by mere accidents of observation. The first and best known specimen of the class, the members of which, on January 1, 1904, numbered 397,[2] anticipates by about a month the rule of annual recurrence.

When Bayer, in 1603, affixed in his charts the Greek letter *o* to a small star in the neck of the Whale, he had no suspicion of its identity with a supposed "Nova" which had disappeared seven years previously, after blazing up to the second magnitude. Its discoverer, on August 13, 1596, was David Fabricius, of Osteel in East Friesland; but though he saw the object again, February 15, 1609, he left it to John Phocylides Holwarda, professor of philosophy at Franeker in Holland, to ascertain its true character in 1639; and the repetition of the phases in cycles of 333 days was established in 1667 by Boulliau.[3] The name "Mira," bestowed by Hevelius upon the changing star in Cetus, commemorates the amazement excited by the detection of stellar periodicity.

The phenomena it presents would seem incredible were they less well established. Once in eleven months the star mounts up in about 125 days from below the ninth to near the third, or even to the second magnitude; then after a pause of two or three weeks, drops again to its former low level in once and a half times, on an average, the duration of its rise. The brightest maximum on record was observed by Sir William Herschel, November 6, 1779, when Mira was little inferior to Aldebaran;[4] the faintest minimum, that of 1783, is said to have carried it below the tenth magnitude. An extent of eight magnitudes may then be assigned to the oscillations of this strange object, which accordingly emits, at certain times, fully fifteen hundred times as much light as at others. That each maximum is a genuine conflagration has been proved by spectroscopic observation; the conflagrations recur yearly, with approximate regularity, and

[1] *Astr. Journ.* No. 193.
[2] *Harvard Circular*, No. 74.
[3] *Monitum ad Astronomos*, p. 7.
[4] *Phil. Trans.* vol. lxx. p. 338.

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after three centuries of notified activity, give no signs of exhaustion!

The height of the maxima, however, varies greatly. The consecutive ones of 1887 and 1888 (represented from Colonel Markwick's observations in Fig. 3) showed a nearly fourfold difference of intensity; but Heis's remark that high and low maxima tend to alternate has not in the long run proved consonant with facts. There is no rule by which the brilliancy of impending phases can be predicted. That of November 1868, in which the star just failed to reach the fifth magnitude, was, it is true, preceded by a high maximum, but several average or low maxima followed it. All that can be said is that exceptionally bright apparitions are isolated; they do not come in sets, but one by one, at considerable intervals,—at

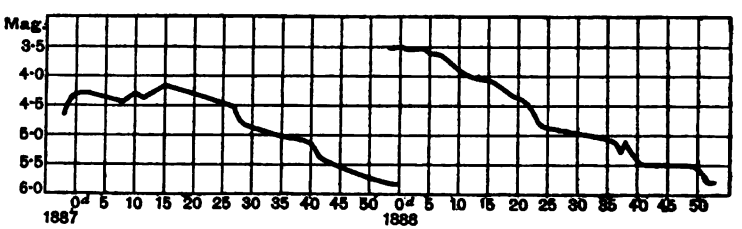

FIG. 3.—Two consecutive Maxima of Mira Ceti.

intervals, if M. Guthnick's conclusion proves correct, of 59½ years. The high maxima of 1779, 1839, and 1898 suggested this period, prescribed—it is thought possible—by extra tidal disturbances due to the periastron passages of a distant satellite revolving in a very eccentric orbit.[1] The next brilliant phase need not be looked for, on this showing, until 1957.

At minimum, Mira rarely descends far below the ninth magnitude. Fig. 4 portrays, from the observations of Mr. Stebbins,[2] the gradations by which it lost and regained light in 1902-3. Although the star appears never to become actually inert, its changes during six weeks amount to no more than flutterings about the lowest level of brightness. The progressive reddening of its rays as they grow dim is held by M. Osthoff to be explicable as a physiological effect.[3]

[1] *Astr. Nach.* No. 3745.
[2] *Astroph. Journ.* vol. xviii. p. 346.
[3] *Astr. Nach.* No. 3940.

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Spectral variations are, nevertheless, evident,[1] and must contribute to the result.

The periodicity of Mira obeys a highly complex law. Deviations to the extent of a fortnight from the "mean period" of 331 days are common, and the maximum of September 29, 1840, was a full month late.[2] Its perturbations may, indeed, be themselves periodical, but if so, their law has not yet been successfully formulated. Argelander detected the influence of a wave of disturbance with an amplitude of twenty-five days, and embracing eighty-eight periods;[3] Schwab's observations indicated subordinate ripples of change in six and a half days;[4] and there are half-effaced traces of several oscillations besides.[5] Yet none are quite securely established. Guthnick, however,

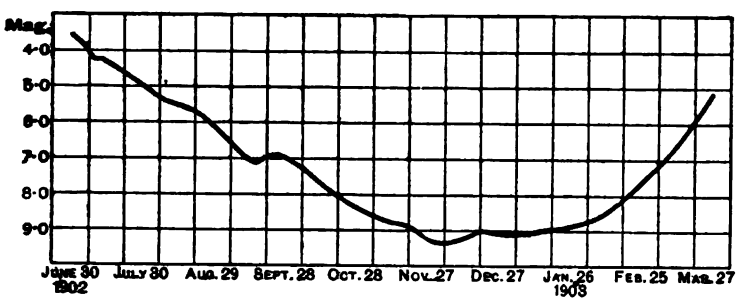

FIG. 4.—Minimum of Mira Ceti, 1902-3.

has entire confidence in the reality of an inequality covering 200 cycles (180 years), which is doubtless the equivalent of one suspected by Argelander with a period of 160 years. The test of verified prediction will eventually decide whether he is right. The *shape* of the light-curve, too, varies notably. Its peaks are sometimes much blunter than at others; and the star, which usually retains its full lustre during a fortnight, has been known to remain twice that time stationary. Still more singularly, the otherwise invariable rule of an increase more rapid than the ensuing decrease was reversed in 1840. Sixty-two days were occupied in ascending from the sixth to

[1] *Astroph. Journ.* vol. xviii. p. 360.
[2] Argelander, *Astr. Nach.* No. 416.
[3] *Bonner Beobachtungen*, Bd. vii. p. 332.
[4] *Astr. Nach.* No. 2731.
[5] Argelander in Humboldt's *Cosmos*, vol. iii. p. 234.

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the third magnitude, forty-nine only in sinking back to the datum level. The anomaly, due to what might be called an unprepared retardation of the maximum, recalls the abnormal course of the sunspot cycle which culminated at the close of 1883.

The spectrum of Mira is a splendid example of Secchi's third type. Eleven bands of profound shadow, sharp towards the violet, gently gradated towards the red, throw out into strong relief the intervening brilliant zones; while dark lines of metallic absorption, and vivid hydrogen-rays, vary the effect, and add to the intricacy of the characters to be deciphered. The more refrangible members of the hydrogen series are those chiefly brightened in this star; no trace of C betrays itself to the most attentive scrutiny; F has never been seen, and is only occasionally photographed.[1] Its violet associate, Hϵ, is also exceedingly dim, either intrinsically, or because of the obscuring effect of a coincident calcium-band. The brilliant phase of Mira in 1898 was attended by a curious triplication of the blue hydrogen-lines,[2] as if through powerful magnetic action. But the phenomenon has not recurred; hence the polarising experiments, by which its nature could be established, have yet to be tried. The dark lines in this spectrum are affected by motion-shifts corresponding to a recession of the star from the earth at the rate of 66 kilometres (40 miles) a second;[3] the bright lines are much less displaced. Yet there is no evidence that the absorption- and emission-rays, although they act thus independently, belong to distinct bodies. Mira is, to all appearance, a singly-constituted star.

The same may be said of a variable in the neck of the Swan, which Bayer, ignorant of its changing character, set down in his maps as of the fifth magnitude. It still retains the name he gave it of "χ Cygni." Missed by Gottfried Kirch in July 1686,[4] it reappeared October 19, and subsequently disclosed to his vigilant watch fluctuations even wider than those of the "wonderful" star in Cetus. It descends below the thirteenth and rises nearly to the fourth magnitude,

[1] Stebbins, *Astroph. Journ.* vol. xviii. p. 364.
[2] Campbell, *ibid.* vol. ix. p. 31.
[3] Stebbins, *ibid.* vol. xviii. p. 352.
[4] *Miscellanea Berolinensia*, t. i. p. 208.

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sometimes indeed stopping short when barely visible to the naked eye, but more commonly remaining lucid for a couple of months. Nor is its course much better regulated as regards time. "Errors" up to forty days often attach to its phases, and the attempt to correct them by the introduction of cyclical terms has proved only partially successful.[1] The period, estimated at 402 days by Kirch, now averages 406. Olbers

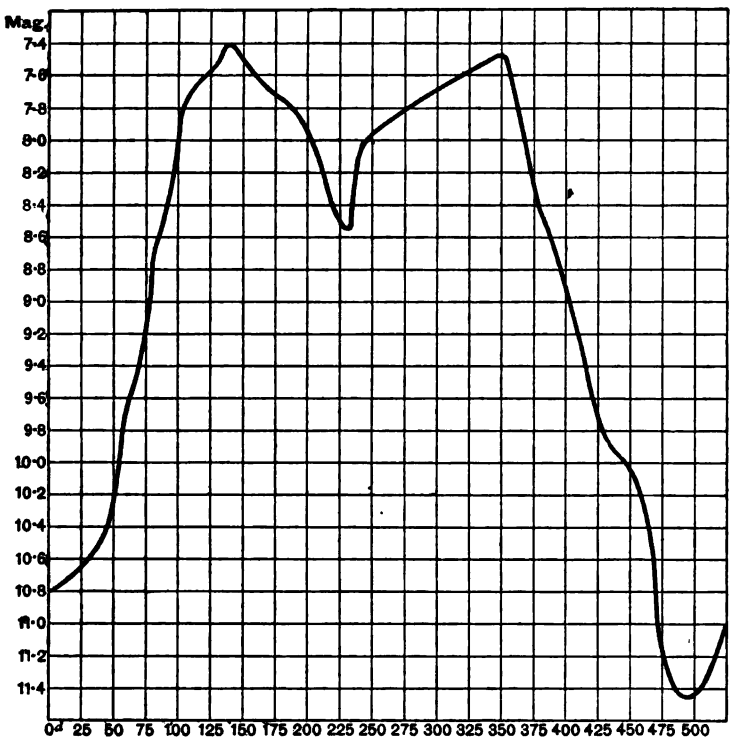

FIG. 5.—Light-curve of R Normæ.

noticed that it had been steadily lengthening down to 1818,[2] and it is lengthening still. The compensatory process anticipated by him has not set in. As usual in such cases, the ascent to maximum is much more rapid than the descent from it, occupying at present about 171 days.[3]

[1] *Bonner Beob.* Bd. vii. p. 336; *Mannheimer Jahresbericht*, Bd. xl. p. 110.
[2] Schumacher's *Jahrbuch*, 1841, p. 93.
[3] Chandler, *Third Catalogue*, 1896.

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The colonnaded spectrum of χ Cygni is appropriate to its scarlet colour. Moreover, on May 19, 1889, when the star was near a maximum, Mr. Espin perceived evidence in it of direct radiation by hydrogen which seems to be quite similarly conditioned to the blaze in Mira. The first and fifth members of the series (Hα and Hϵ) are missing; the second (Hβ) is perhaps less evasively present. There is besides a discrepancy in the positions of the bright and dark systems of lines analogous to that perceived in the spectrum of Mira,[1] and obviously connected with the peculiar processes of light-change characteristic of such stars.

The light-curve of R Normæ is depicted in Fig. 5 from Mr. Innes's observations in 1898-99 at the Royal Observatory, Cape of Good Hope.[2] It is of a very unusual character.

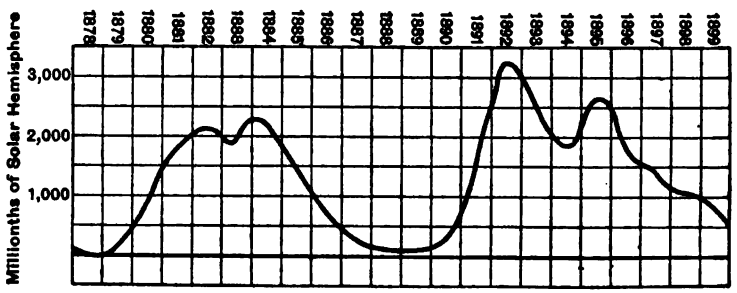

FIG. 6.—Areas of Faculæ on the Sun, 1878-99.

Each cycle includes a pronounced double maximum, resulting, we can scarcely doubt, from the full and unrestricted development of a tendency, half-suppressed in most variable stars, to arrest the ebb of light at a certain interval after the culminating crisis. The vicissitudes of solar agitation, too, undergo a similar phase of hesitancy, as may be gathered from Fig. 6, which portrays, from the Greenwich observations, the virtually double facular maxima of 1882 and 1884, and of 1892 and 1895. The variability of R Normæ was first noted by Gould in 1871. An average period of 481 days is conformed to; but extensive divagations from it are patent.

They are, however, insignificant compared with those of

[1] Eberhard, *Astr. Nach.* No. 3765; *Astroph. Journ.* vol. xviii. p. 198. *Annals of the Cape Observatory*, vol. ix. p. 107 B.

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U Lupi. Indeed, this star barely pretends to regularity. Sometimes, it is true, the sudden failures of light distinguishing it succeed each other at intervals of about eighty-seven days; but an interruption is sure to supervene, baffling all attempts at anticipation, and the oscillations are then resumed as if by a fresh impulse. In Fig. 7 two successive minima are represented—one complete, the other seemingly abortive. Mr. Innes discovered this singular object in 1898,[1] through its unexplained absence from the Cape Durchmusterung plates, and watched the caprices of its instability during three years.

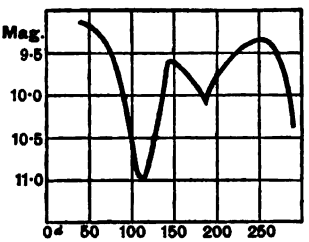

FIG. 7.—Light-curve of U Lupi (Innes).

By far the longest period yet attributed, on reasonably good evidence, to a variable star was assigned to ϵ Aurigæ by Dr. Ludendorff of Potsdam in 1903.[2] As a white star with a spectrum resembling that of α Cygni, it should not be predisposed to instability; and the amplitude of its changes is, in fact, of no more than seven-tenths of a magnitude, implying a reduction of brightness by one-half. Moreover, they take place very gradually, and are rarely observed. For the most part, the star shines with approximate constancy at 3·3 magnitude. Its phases of dimness were believed to occur quite irregularly, until Dr. Ludendorff showed, by an exhaustive discussion, that they are subject to a periodicity of slightly more than twenty-seven years. Decline and recovery occupy thirteen or fourteen months; an intervening stationary time of least light lasts just ten; so that the entire oscillation needs close upon two years for its accomplishment. Three were recorded in the nineteenth century, a fourth in 1901-2. It remains to be seen whether future minima will honour the cheques of calculation as they fall due. Illusory effects of periodicity have often been perceived in stars fundamentally irregular, and ϵ Aurigæ may still evade the law of order which it has temporarily obeyed. Its character as a spectroscopic binary, established by Drs. Vogel and Eberhard in

[1] *Astr. Journal*, No. 442.
[2] *Astr. Nach.* Nos. 3918-20.

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1902,[1] cannot well be supposed extraneous to its luminous variability; but the mode of connection remains enigmatical, since the occurrence of eclipses is precluded by the conditions of movement that appear to prevail in the system.[2]

We now come to that unique star, η Carinæ. Its actual appearance is insignificant. Invisible to the naked eye, it is telescopically distinguished only by its reddish colour and slightly superior brightness from the crowd of small stars embroidering one of the finest of the southern nebulæ, named the "Key-hole Nebula," from the aperture of that shape with which it is centrally perforated. Close to one edge of the aperture, in the densest part of the nebula, η Carinæ is placed. Nor can we suppose its position fortuitous. There is every reason to believe the star to be really plunged in nebulous substance; and the peculiarity of its environment combines, we must suppose, with peculiarities of constitution to produce the exceptional character of its changes.

The first observation of η Carinæ was made by Halley at St. Helena in 1677, when it was of the fourth magnitude; had it been as bright in the second century A.D., Ptolemy would presumably have recorded it, since, as Mr. Innes points out,[3] the chief stars in Crux and the Centaur, which culminate about the same altitude, are included in the Almagest.

Soon after the young English astronomer made his hurried survey of the southern sky, the variable had a notable accession of lustre. Père Noël, a Jesuit missionary in China, rated it as of the second stellar rank, 1685-89,[4] and so it appeared to Lacaille in 1751; yet the discrepancy with Halley's appraisement remained unnoticed. The higher estimate was confirmed by those of Fallows, Brisbane, and Johnson in 1822, 1826, and 1832 respectively, an intervening decline having been noted only by the traveller Burchell, who, familiar with the star as of the fourth magnitude in 1811-15, was surprised one night in 1827, at San Paolo in Brazil, to see it temporarily raised to a level with the finest brilliants

[1] *Sitzungsberichte*, Berlin, November 27, 1902.

[2] A. M. Clerke, *Observatory*, vol. xxvii. p. 118.

[3] *Annals Cape Observatory*, vol. ix. p. 75 B. Henderson is referred to as the author of the remark.

[4] Winnecke, *Astr. Nach.* No. 1224; Klein, *Sirius*, Bd. vi. p. 285.

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of the sky. Another, and a still more vigorous outburst, was witnessed by Sir John Herschel, December 16, 1837. Without previous note of warning, the star all at once nearly tripled its light, and before the end of the year fully matched α Centauri. Since then it has been kept under strict surveillance as a notorious character, and not without reason. After a partial decline and several preliminary "flutterings," it reached a final maximum in April 1843, when Sirius alone among the fixed stars slightly outshone it. This high position was moreover fairly well maintained for nine or ten years. Gilliss, at Santiago in 1850, found it very little inferior to Canopus in light, and in colour more deeply tinged with red than Mars.[1] Still of the first magnitude in 1856,[2] it fell to the second in 1858, to the third in 1859, and ceased to be visible to the naked eye early in 1868.[3]

For sixteen further years the slow ebb of light continued, and the magnitude of the once effulgent orb, carefully determined by Mr. Finlay at the Cape, was in March 1886 only 7·6.[4] This proved to be the beginning of a stationary minimum of indefinite duration. The star has suspended its fluctuations, and it is impossible to say when it may resume them. Quite probably its history is one that "does not repeat itself." Our continuous knowledge of it is embodied in the accompanying diagram (Fig. 8). A single vast oscillation is indicated, occupying about a century for its completion, and diversified by secondary fluctuations of a very conspicuous character (innumerable minor ones are ignored in the figure). The data at present available, however, afford no grounds for concluding this oscillation to occur regularly. Attempts to assign a period to the variations of this object have signally failed. Wolf's of forty-six,[5] and Loomis's of seventy years,[6] were both palpably too short; larger time allowances encountered obvious difficulties; and η Carinæ was, by general consent, abandoned to its own lawless courses. Protracted periods of light-change have, in several other cases, been suggested,

[1] Abbott, *Monthly Notices*, vol. xxi. p. 230.
[2] Moesta, *Astr. Nach.* No. 1054.
[3] Tebbutt, *Monthly Notices*, vol. xxxi. p. 210.
[4] *Monthly Notices*, vol. xlvi. p. 340.
[5] *Ibid.* vol. xxiii. p. 208.
[6] *Ibid.* vol. xxix. p. 298.

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but have in none been verified, unless Dr. Ludendorff's of twenty-seven years for ϵ Aurigæ prove an exception. The stars they were ascribed to, when the time came for a repetition of their presumed cyclical changes, showed a total want of conformity with what was expected of them. As examples may be mentioned 63 Cygni, to which Mr. Espin attributed a period of five, and R Cephei, thought by Mr. Pogson to obey one of seventy-three years.

Thus the great southern variable cannot be depended

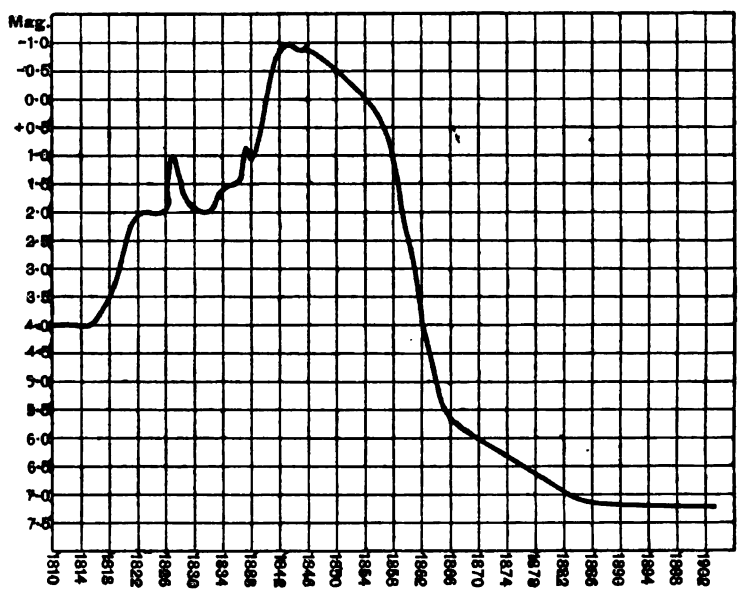

FIG. 8.—Light-curve of η Carinæ, 1810-1902.

upon to revive its past splendours. There is nothing inevitable about the kind of fluctuation it exemplifies. One might indeed say of it, in Jack Cade's phrase, "then is it in order when it is most out of order." Irregular light-change seems to develop all its resources in the vicissitudes of η Carinæ. They have included quick, yet sustained ascents in brightness, and also evanescent kindlings. Stationary epochs have been followed by epochs of instability; at some times the star has shown a tendency to establish itself at halting-places, at others to slip along an inclined plane of change. In all this it differs materially from temporary stars, which leap up, as if

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by a single impulse, to their solitary maximum, after which they lose in a few months the whole of the light they had acquired. The nature of its light, on the other hand, assimilates it to the temporary class. Sir David Gill's study of photographs taken with the McClean apparatus in 1899 demonstrated a close agreement between the spectra of the smouldering variable and of Nova Aurigæ when near maximum.[1] Hydrogen-lines, broad and bright, with dark companions on their more refrangible sides, were the leading feature of both; and a feature no less enigmatical in the one case than in the other. Yet the fact, as already remarked, is of profound importance that the conditions transiently present in Novæ have been rendered permanent both in η Carinæ and in P Cygni, the quasi-Nova of 1600, now an unexceptionally steady fifth-magnitude luminary.

Among the miscellaneous objects comprised in Pickering's third class of variables are some slightly changeable third-type brilliants. Sir William Herschel added in 1795 α Herculis to the list of seven fluctuating stars then known.[2] A period of two months assigned by him to its oscillation between 3·1 and 3·9 magnitudes has proved illusory. During some years the swing appears almost to cease, then is hurriedly resumed, but with no settled order. The analogous variations of Betelgeux and β Pegasi are equally unmethodical. A conspicuous brightening of the former star attracted much attention in the autumn of 1902, but speedily subsided.

The extraordinary character of a star long known as "Variabilis Coronæ," now called "R Coronæ," was discovered by Pigott in 1795; a near neighbour of the "blaze star" of 1866, its changes are of the nature of extinctions rather than of outbursts. Ordinarily of 5·5 magnitude, it occasionally drops out of sight with small telescopes, and after lingering below the tenth, or even the twelfth magnitude for many months, slowly regains its lost light. But its phases, at times suspended, as during the seven years, 1817-1824,[3] are

[1] *Monthly Notices*, vol. lxi. p. 456, App. iv.; cf. *Harvard Annals*, vol. xxviii. p. 175 (Miss A. J. Cannon).

[2] *Phil. Trans.* vol. lxxxvi. p. 452.

[3] Argelander, *Bonner Beob.* Bd. vii. p. 374; Olbers, *Berliner Jahrbuch*, 1841, p. 100.

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at others ill-marked. Thus at the minimum observed by Sawyer, October 13, 1885, the star was still of 7·4 magnitude.[1] It shows a peculiar spectrum needing closer investigation.

R Cephei is a star which, since the beginning of the present century, has lost $\frac{39}{40}$ of its radiance, and at present in no way tends towards recovery. In the time of Hevelius it was of the fifth magnitude, and Groombridge's observation of it in 1807 showed it to be then still unchanged. By 1840, however, it had sunk to the tenth, and has never since risen above the eighth magnitude.[2] Its identity with the "24 Cephei" of Hevelius, tracked out by Pogson in 1856,[3] is universally admitted. Of late years it has shown no sign of variability. Its light, considered by Schönfeld to be tinged with red, appeared bluish to Farley in 1838.

Genuinely red stars are ordinarily subject to shiftings of photometric standing. Among twenty-two such, kept in view by M. Safarik at Prague, from 1883 to 1888, for the express purpose of testing their constancy, only nine remained without noticeable change, two were found periodically, six irregularly variable, and five either vanished or lost great part of their light. Earlier observations of several of these objects certified the progress of their decline during twenty to twenty-five years.[4] An example of a sudden acquisition of lustre is afforded by a small red star in the same field of view with γ Cygni. Between December 1885 and June 1886, Mr. Espin perceived it to have risen in rank by a whole magnitude,[5] that is, to be giving out two and a half times as much light as six months previously. And so far as is known the gain has been kept.

The track of recent astronomical progress is strewn with the dilapidated remnants of hypotheses invented to explain the strange phenomena of stellar variability. Nevertheless, much has been learnt as to their relationships and essential nature. The gaseous incandescence, for instance, visible in

[1] *Astr. Journ.* No. 151.

[2] Schönfeld, *Mannheimer Jahresbericht*, Bd. xl. p. 113; Gore's *Catalogue*, (1884), p. 200.

[3] *Monthly Notices*, vol. xvii. p. 23.

[4] *Astr. Nach.* No. 2874.

[5] *Journal Liv. Astr. Soc.* vol. v. p. 2.

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the spectra of periodical stars near their maxima brings them into such close physical relationship with temporary stars as absolutely to prohibit the speculative separation of the two kinds of change they respectively exhibit. A theory stands self-condemned which deals with them on different principles. Moreover, the association of variability with processes of luminous change in stellar atmospheres has been rendered obvious; and this at once disposes of darkening expedients, as by slag-formation, vaporous obscurations, and axial rotation, bringing bright and dark sides alternately into view. Equally inadmissible is the rationale of stellar fluctuations by intermittent chemical associations and dissociations at the atmospheric outskirts of cooling bodies.[1] For the increase of light at maximum demonstrably ensues upon a real access of incandescence, and is not a mere appearance due to the dissipation of absorbing vapours. The fires really die down and leap up at regular intervals; they are not merely screened off and disclosed.

Attempts have several times been made to explain the periodicity of stars through the influence of satellites revolving round them in highly eccentric orbits. Klinkerfues suggested great atmospheric tides, raised at successive perihelion-passages,[2] as a means of bringing about periodic interceptions of light. Plassmann's[3] view of tidal effects is wider, and perhaps embraces a partial truth. For, just as in the earth the unequal attractions of sun and moon on its centre and surface sometimes provoke, though they could not produce, earthquakes, so the tide-raising power of bodies making very close approaches to stars in a critical state of heat-equilibrium may serve as the occasions of luminous outbursts of a temporary or recurrent nature.

Sir Norman Lockyer's meteoritic hypothesis included the pregnant idea that variables are to be regarded as "incipient double stars."[4] But it had a different application to that imagined for it by its author. There is no sound reason for

[1] Brester, *Essai d'une Théorie du Soleil et des Étoiles Variables*, Delft, 1889.

[2] *Göttingische Nachrichten*, 1865, p. 3; see also Dr. Wilsing's comments in *Astr. Nach.* No. 2960.

[3] *Die Veränderlichen Sterne*, Köln, 1888.

[4] *Proc. Royal Society*, vol. xliv. p. 80.

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believing stars like Mira to be composed of twin meteor-swarms blazing through periastral collisions. That their luminosity may be affected by the tide-raising power of unseen companions, it would indeed be rash categorically to deny; yet there is no evidence to support the opinion, while the periodicity of the objects in question is of so disturbed a kind as to raise almost insuperable obstacles against connecting it with movements necessarily punctual. Moreover, periodical cannot be sharply divided off from irregular variables. Every degree of perturbation, up to the total subversion of laws of change, is met with among them. Many stars seem at times disposed to conform to a period which they later ignore. In others, method is indicated, though too vaguely to be defined, while the majority oscillate, with wide allowance of amplitude, about a period itself often subject to periodical or secular change. It is evident that the immediate and unmodified interaction of revolving masses cannot explain breaches of regularity widening out to its total destruction.

The time has scarcely yet come to formulate a general theory of stellar variability, but we may, at any rate, try to render our ideas on the subject coherent, admitting provisionally those that are consistent with known facts, rejecting summarily those that contradict them. It will then become possible to realise with some distinctness the conditions under which alone any such theory could be regarded as adequate.

As long ago as 1852, M. Rudolf Wolf adverted to the analogous character of the curves representing sunspot frequency and stellar light-change.[1] They are not only of the same general form, but they are marked by precisely the same kind of irregularities. Both are steeper in ascent than in descent; both rise into peaks of unequal heights at unequal distances apart. Mira, χ Cygni, R Hydræ, and the rest, have, like the sun, retarded and accelerated, high and low or abortive maxima. The representation in Fig. 9, from the Greenwich observations, of the changes in sunspot frequency during the decennial period 1867-1877, is the very counterpart of the light-curve of a variable star. Especially characteristic is the break in the descending branch reflecting a partial recovery

[1] *Mittheilungen Naturforsch. Gesellschaft*, Bern, 1852, p. 261.

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in the downward course towards minimum, to which variable stars of different classes are prone, and which may even, as in R Normæ, assume the importance of a second co-ordinate maximum. Moreover, the flow of change in sun and stars alike is broken and disturbed by the superposition upon the normal period of subordinate and superior cycles ranging from a few days perhaps to centuries.

The presumption then of their similar origin is very strong: nor are we wholly without evidence of a physical nature to the same effect. The development of bright lines in the spectra of variable stars near their maxima is paralleled

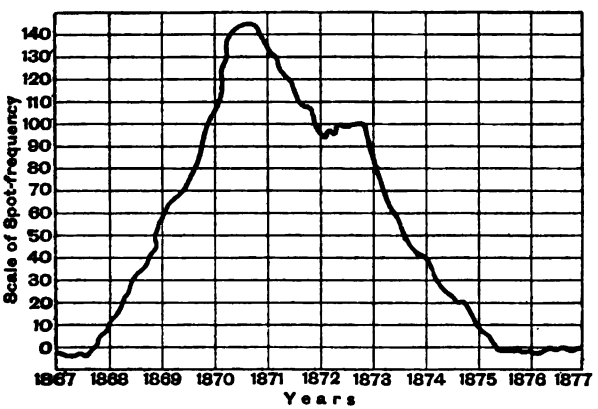

FIG. 9.—Curve of Sunspot Frequency, 1867-77 (Ellis).

in the sun by the increase of emissive intensity in the corona as sunspots increase, as well as by the attendant development of calcium flocculi shining by direct radiation. Atmospheric incandescence is thus in both cases heightened, although in immensely different degrees; and confirmation is afforded to what was already certified by the congruous shapes of the two curves, namely, that the maximum of spots in the sun corresponds with the maximum of light in stars, and *vice versâ*. It is the more necessary to bear this in mind, because obscurations by spots have sometimes been alleged as a cause of stellar variability. That just the opposite is the truth has been further certified by a beautiful mathematical investigation set on foot by Professor Turner in 1904.[1] Submitting

[1] *Monthly Notices*, vol. lxiv. p. 543.

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to the methods of harmonic analysis stellar light-curves and the curve representing solar cyclical activity, he obtained results of emphatic import as to the identity (it might be said) of the constructive principle at their base, provided that maxima of spots be regarded as the correlatives of maxima of brightness. But the agreement vanished when the trial was made of inverting the relationship.

The conclusion that solar and stellar disturbances are alike in kind clears the ground for further investigation, for, besides obliging us to reject causes for the latter which are demonstrably unconcerned with the former, it renders sunspot studies directly available for solving the problem of stellar variability. Now what do we really know about the production of sunspots? Not much more than that they arise incidentally to the great circulatory process by which photospheric radiations are maintained. They arise, beyond question, when it is most active and tumultuous. Nor is there anything to show that the variation in their numbers depends upon an external cause. It seems, on the contrary, to result from peculiarities inherent to the solar constitution—from the intricate movements proceeding within the vast globe, and accommodating themselves somehow to those due to the swirl of its rotation—from fluctuating relations of heat and pressure — from the alternate accumulation and discharge of explosive forces, perhaps of a molecular nature. Similarly, the secret of stellar light-vicissitudes is held by the stars themselves, although superinduced modifications may also, in some cases, be recognised. But that their periodicity is essentially self-regulated becomes manifest through the consideration that it is materially influenced by colour. Not only a very large proportion of red stars are variable, but nearly all variables of long period are red. The length of the period, too, is very distinctly connected with the intensity of the colour. This was first noticed in 1873 by Dr. Schmidt of Athens;[1] it was reaffirmed by Mr. S. C. Chandler, who concluded, after an elaborate study of all the facts, that "the redness of variable stars is, in general, a function of the lengths of their periods of light variation. The redder the tint the longer the period."[2] And Mr. Yendell has quite lately

[1] *Astr. Nach.* No. 1897. [2] *Astr. Journ.* Nos. 186, 193.

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reached a similar conclusion.[1] Many individual exceptions to the rule might be cited. But it prevails in a large sense; and its prevalence enforces the obvious truth that the explanation of redness in stars lies very close to the explanation of their variability in long periods.

[1] *Astr. Journ.* No. 564.

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CHAPTER IX

VARIABLE STARS OF SHORT PERIOD

We have seen, in the last chapter, that stars varying their light in periods of less than thirty days stand apart in several important respects from those undergoing slower changes. The distinction is accentuated by the tendency apparent in each class to group its members as far as possible from the frontier-line of separation. Thus, most long periods exceed two hundred days, while a large majority of short periods fall below eight. The total number of stars so far found to be variable within a calendar month is eighty (besides a multitude of faint objects crowded together in clusters); of these seventy complete an oscillation in less than ten days, while sixteen have periods measured by hours. Fig. 10 gives a graphical conspectus of these facts.

Variables of short period are, as we have said, nearly all white or yellow stars, showing spectra of the Sirian or solar type. They fluctuate much less extensively and much more precisely than Mira-variables. In many rapid stars the light ebbs and flows like clockwork as to time, and as to measure, with deviations scarcely of the tenth of a magnitude from a settled standard. These remarkable changes progress gradually and continuously in Pickering's fourth class of variables; in his fifth class they only interrupt, although at perfectly regular intervals, the usually steadfast shining of certain stars. Of these two kinds the former is conspicuously exemplified in β Lyræ—a star of which we have already made the acquaintance in connection with its gaseous spectrum—the latter in Algol.

Further distinctions, however, have to be made. Class IV. really comprises three separate families, which may conveni-

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ently be designated as Cepheid variables, Cluster variables, and Geminid variables. Their several characteristics we shall now briefly indicate.

One peculiarity, full of meaning in itself and in its implications, is common to them all. They are, probably without exception, close binary systems revolving in the period of light-change. This was long ago suspected of stars undergoing brief phases of obscuration; and the fact, as regards Algol, was definitely ascertained by Dr. Vogel in 1888. About thirty analogous objects are already known, and there is slight

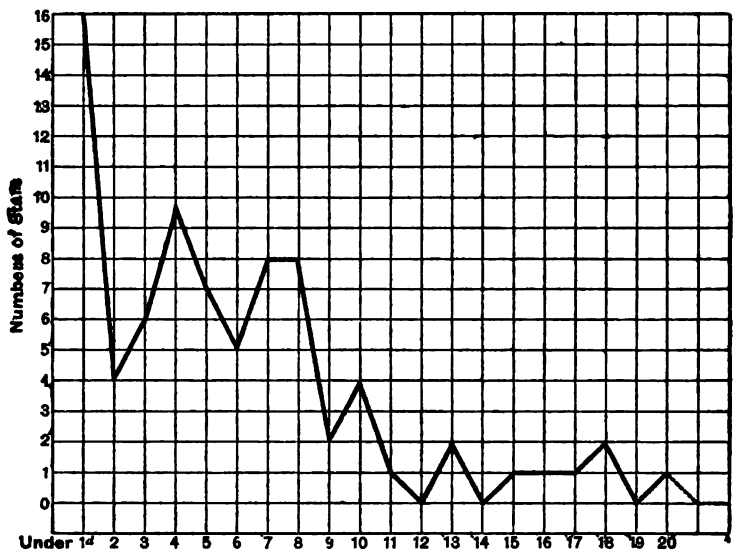

FIG. 10.—Distribution of 80 Variable-Star Periods under 20d.

risk of error in describing them generically as "eclipsing stars." Far more surprising was the discovery that stars fluctuating in a manner inconsistent with the eclipse hypothesis shared, nevertheless, their compound nature. Take, as an example, δ Cephei, the light-curve of which is depicted in Fig. 11. It is by no means symmetrical. The ascending is much steeper than the descending branch, and the latter is besides markedly inflected. Now the great majority of sporadically occurring short-period variables belong to the type thus illustrated. In many, it is true, the pause in the decline from maximum is feebly accentuated or imperceptible; but most gain brightness about

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twice as quickly as they part with it, and all accomplish their changes by uninterrupted gradations. They are continually on the move; they have no definite halting-places, either at maximum or at minimum. This mode of variation is clearly irreconcilable with eclipse-conditions, and the anticipations of reason have been confirmed by experience. Yet the objects in question are, in point of fact, binary stars, and their revolutions strictly control their light-changes. This is known from the synchronism of the two kinds of observed effect—of the spectroscopic alterations due to orbital movement, and of the photometric periodicity. The variable radial velocity of δ Cephei was detected by Bélopolsky in 1894;[1] and that of η Aquilæ, a star similarly variable, in the following year.[2] In both systems the companion-body is obscure; in both the occurrence of eclipses is precluded by the circumstances of

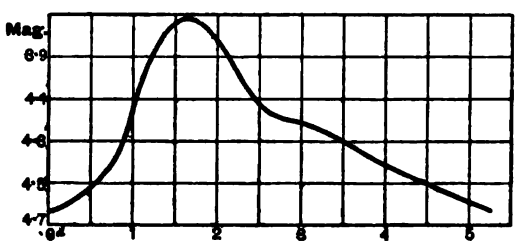

Fig. 11.—Light-Curve of Delta Cephei.

movement. Both stars give spectra of the solar type. The further recognition, as spectroscopically double, of the Cepheid variables, X, W, and Y Sagittarii,[3] of T Vulpeculæ[4] and S Sagittæ, adds weight to the accumulating evidence that the peculiarity may be generalised. There need be no hesitation in affirming that the pattern of variation set by δ Cephei is prescribed by the circling, in an identical period, of a usually non-luminous companion.

"Cluster variables" are met with by the score in certain globular clusters, and scarcely at all in the open sky. Hence their current title. Their discovery by Professor Bailey in

[1] *Astr. Nach.* No. 3257; *Astroph. Journ.* vol. i. p. 160; *Bull. de L'Acad. de St. Pétersbourg*, Nov. 1894, No. 3, p. 268.

[2] *Astroph. Journ.* vols. vi. p. 393 (Bélopolsky); ix. p. 59 (Wright).

[3] Slipher, *Bulletin of the Lowell Observatory*, No. 11; R. H. Curtiss, *Lick Bull.* No. 62.

[4] Frost, *Astroph. Journ.* vol. xx. p. 296.

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1895 remarkably illustrated the perfection to which the photographic method has been brought. To individualise the minute, thronging components of compressed clusters would, until lately, have been regarded as a notable feat; to follow their variations of lustre through brief cycles of about twelve hours, and to determine their special character, might well have seemed impossible. The camera alone is competent to undertake work at once so delicate and so comprehensive. With two or three of the most powerful telescopes in the world, these tiny light-specks can, indeed, be observed to good purpose (as Professor Barnard has shown); but only

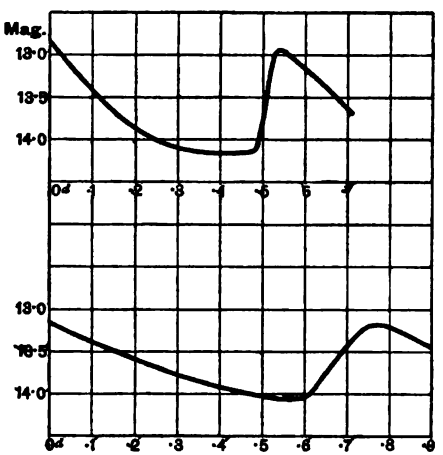

FIG. 12.—Typical Light-Curves of Cluster Variables.

one by one, and they demand wholesale treatment. Some star-globes contain shoals of variables; over 500 have so far been registered, besides upwards of a thousand in the Magellanic Clouds.[1] The variations of stars in clusters, moreover, are by no means vague or indeterminate. They are executed with punctuality and precision in periods, very generally, of less than one day. Three light-curves, two typical and one individual, are shown in Figs. 12 and 13. They are copied from Professor Bailey's drawings illustrative of his elaborate discussion of the conditions of variability in the great southern cluster ω Centauri.[2] And they are, in all

[1] Pickering, *Harvard Circular*, Nos. 82, 96, 100.
[2] *Harvard Annals*, vol. xxxviii. 1902.

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such groups, strangely uniform. A swift rise to maximum, and a prolonged halt at minimum, are their leading traits. Cluster variables are distinguished from Cepheid variables, partly by the suddenness of their upspringing, but most essentially by the relatively protracted duration of their dim phases. About half of each period is spent at a dead level of low light; then all at once tripled brightness supervenes, to ebb away again by slower gradations.

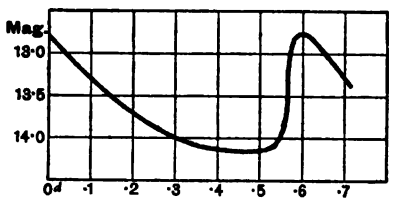

Fig. 13.—Light-Curve of No. 45 Omega Centauri.

Why stars thus singularly affected should so strongly tend to herd together, none can at present attempt to divine; but the exceptions to the rule of aggregation claim particular attention, if only for their rarity. One of them is S Aræ, noticed as variable by Mr. Innes in 1898.[1] The curve by which he delineated its course of change is copied on a reduced

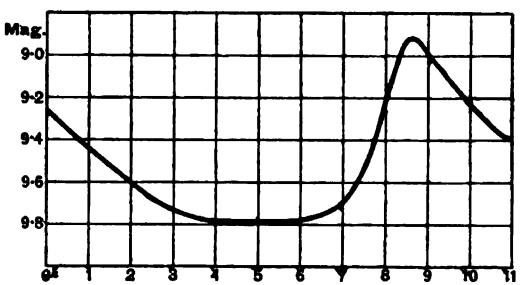

Fig. 14.—Light-Curve of S Aræ.

scale in Fig. 14. Scarcely distinguishable from one of Bailey's typical tracings for the variables in ω Centauri, it shows a stationary minimum lasting four hours, then a more than twofold increase of lustre within an hour and half, followed by a leisurely decline in approximately five and a half, by which the cycle of nearly eleven hours is completed. Y Lyræ is almost the *alter ego* of S Aræ. Mr. Stanley Williams determined its period to be $12^h\ 4^m$, the rise from 11·3 to 12·3

[1] *Cape Annals*, vol. ix. p. 126B; *Astr. Journ.* Nos. 491-92 (Roberts); *Monthly Notices*, vol. lxi. p. 163.

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magnitude being accomplished in $1^h\ 30^m$; and he has since associated with it a star in Cygnus (designated "UY Cygni") following nearly the same prescription of change.[1] Madame Ceraski's cluster-variable, also situated in Cygnus, is believed to have the extraordinarily short period of $3^h\ 12^m$, and an oscillation-amplitude of approximately one magnitude. Discovered photographically in 1904, it demands special and adroit study.

The third sub-class of short-period variables, called "Geminids" from their exemplar ζ Geminorum, alter in brightness by continuous and symmetrical gradations. Their maxima are placed about midway between their minima. All (we need not hesitate to say) are binary systems, but some at least are exempt from eclipses. The line, however, separating them from occulting variables is very feebly traced. Whether or no eclipses occur has to be decided by a distinct investigation for each individual star, and the process of decision advances slowly. Only in one case a conclusive reply has been obtained, and it is in the negative. Bélopolsky and Campbell independently, in 1898,[2] recognised ζ Geminorum as a spectroscopic pair revolving in the period of light-change ($10^d\ 4^h$). One component is invisible, yet the observed minima are not due to its intervention, since their epochs are not those of conjunction. Eclipses can naturally only take place when the two bodies concerned are in the same line of sight; and the spectroscope intimates their being in the same line of sight by the reduction to zero of their radial velocity. They must, in other words, at the time of occultation, be moving across the line of sight. The non-fulfilment of this condition by ζ Geminorum excludes it peremptorily from the number of eclipsing variables.

The light-curve of U Vulpeculæ (see Fig. 15)[3] so closely imitates that of ζ Geminorum that we need have no doubt of the stars being similarly circumstanced. S Antliae, formerly taken for an Algol variable, belongs to the same category. At its maxima the flow of change is so slack as to suggest an

[1] *Monthly Notices*, vols. lxiii. p. 304; lxv. p. 586.

[2] *Astr. Nach.* No. 3565; *Astroph. Journ.* vols. ix. p. 86; xiii. p. 90.

[3] Müller and Kempf, *Astr. Nach.* No. 3483; Luizet, *ibid.* No. 3570; *Harvard Circular*, No. 41.

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actual standstill, while the minima are comparatively sharp, and the entire cycle is accomplished in $7^h\ 47^m$. It has yielded, so far, no spectroscopic signs of duplicity.

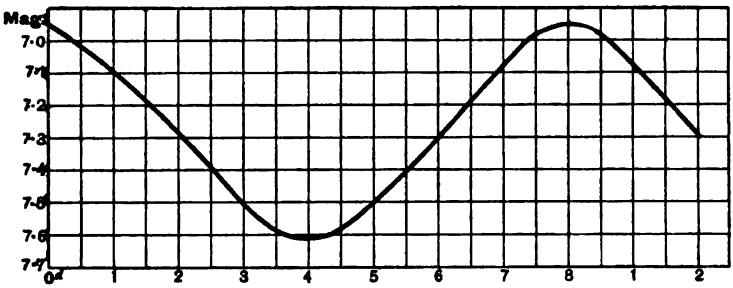

FIG. 15.—Light-Curve of U Vulpeculæ.

Some Geminid stars are subject to what may be called a double periodicity. They dip, that is to say, to a secondary minimum placed half-way between two equal maxima. This mode of variation is brilliantly illustrated in β Lyræ, the saddle-back curve of which is shown in Fig. 16. Its fluctua-

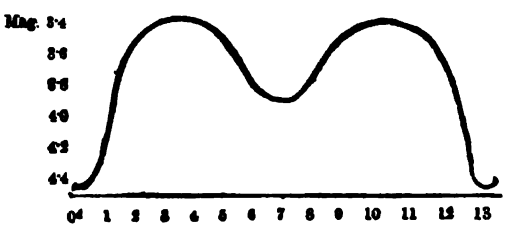

FIG. 16.—Light-Curve of β Lyræ (Argelander).

tions, detected by Goodricke in 1784, were completely tracked out by Argelander in 1844.[1] Their cause is nevertheless still involved in perplexity. The star is known to be binary, but the complex changes in its bright-line spectrum profoundly embarrass measurements of its velocity. The evidence at hand does not preclude the hypothesis of disparate obscurations at the primary and secondary minima respectively; it does not, however, enforce it, and a solution to the enigma presented by this star will perhaps be most easily obtained by the indirect means of studying it at second-hand in analogous objects of less complicated relationships.

[1] *De Stellâ β Lyræ Disquisitio.*

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One such is found in V Puppis, the light-curve of which, as drawn by Mr. A. W. Roberts, is shown in Fig. 17. Its similarity with that of β Lyræ does not need to be pointed out. If the occurrence of a double eclipse can be proved in one case it may be presumed in the other. A spectroscopic pronouncement on the point is awaited with much interest, and should not be difficult to procure. Already, in 1895, V Puppis was ascertained by Professor Pickering to be a spectroscopic binary, composed of two unequally bright stars.[1] Nevertheless we are still ignorant as to whether their movements satisfy the requirements of the occultation-theory. Meantime the photometric data collected by Mr. Roberts have been shown by him to agree remarkably well with the light-variation resulting from the mutual eclipses of two bodies

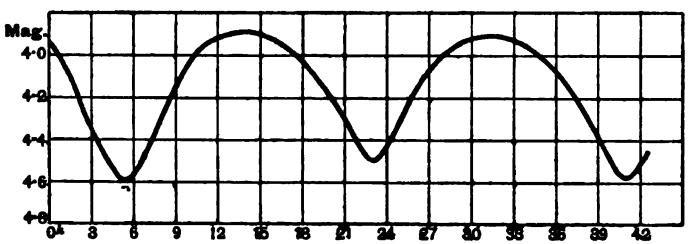

FIG. 17.—Light-Curve of V Puppis.

circulating in contact.[2] Actually in contact they should be, perhaps even confluent; but this involves no mechanical impossibility. It would, however, involve the consequence that the mean density of the double globe of V Puppis could not exceed $\frac{1}{200}$ that of the sun. Other analogues of β Lyræ are U Pegasi, R Sagittæ, with a period of 7·0, and V Vulpeculæ, accomplishing its changes in 7·5 days.[3] That the spectroscope will eventually supply evidence of their binary character is scarcely doubtful, but it does not follow that all or any of them are eclipsing binaries.

We would now invite our readers' attention to the five light-curves grouped together in Fig. 18. They are copied from an instructive paper presented by Mr. A. W. Roberts of

[1] *Harvard Circular*, No. 14.
[2] *Astroph. Journ.* vol. xiii. p. 181.
[3] *Astr. Nach.* No. 3929 (Stanley Williams).

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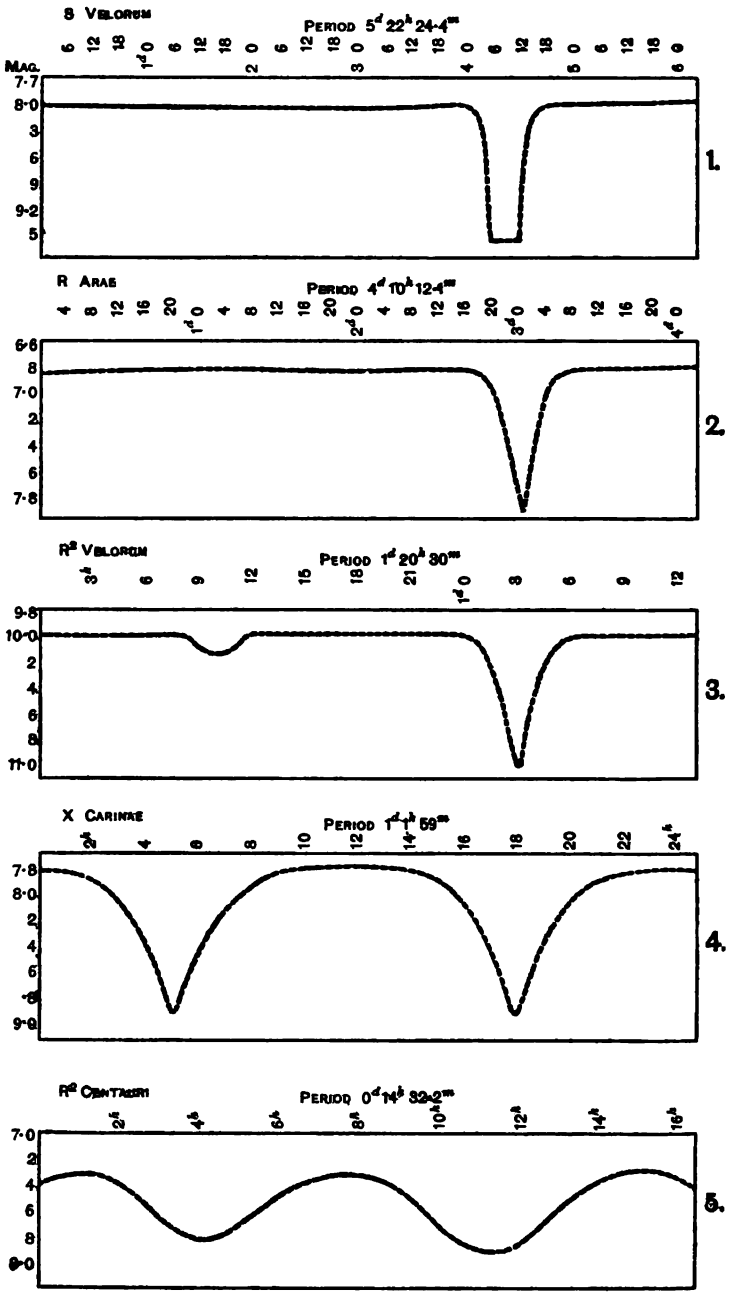

Fig. 18.—Light-Curves of Five Algol Stars.

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Lovedale to the South African Association for the Advancement of Science at its first meeting in 1903. It embodies his principal conclusions regarding stellar eclipses, and vividly illustrates both the variety of conditions under which they take place and the difficulty of pronouncing, in certain cases, for or against their genuine occurrence. Thus, the light-curve of R^2 Centauri (No. 5, the lowest in the diagram) is that of a Geminid star. The stationary maximum characteristic of Algol variables is absent. Mr. Roberts, nevertheless, considers the star to be composed of two egg-shaped bodies rotating on a common axis in $14^h\,32^m$, and sending us more or less light according as we see them broadside or end-on.[1] The forms corresponding to the observed variations in brightness

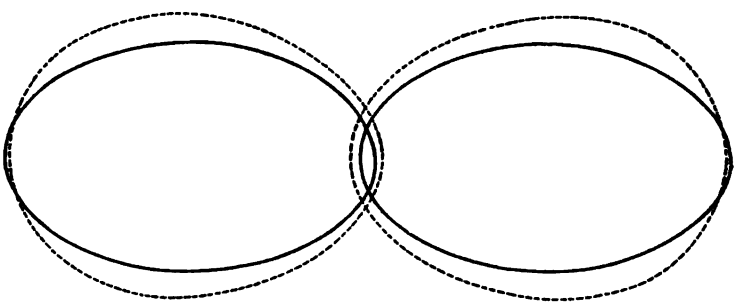

FIG. 19.—System of R^2 Centauri (Roberts).

are depicted in Fig. 19, the dotted lines indicating Darwin's figure of equilibrium for a liquid globe on the brink of fission through accelerated rotation. The close agreement between the forms arrived at from photometric and mechanical considerations respectively is of strongly persuasive import.

Curve No. 4 in our figure is of an intermediate type. X Carinæ verges towards the condition of unceasing change visible in β Lyræ and S Antliae; yet brief intervals of stable shining appear to interrupt the processes of decline and recovery, which Mr. Roberts expounds as the phases of a protracted double eclipse. Two stars, somewhat unequally brilliant, are believed to be concerned in them, the minima being slightly unequal. The orbital period of 26 hours thus includes two light-periods.

[1] *Astr. Journ.* Nos. 378, 384; *Astroph. Journ.* vol. x. p. 312; *Monthly Notices*, vol. lxiii. p. 527.

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The variability of R^2 Velorum, suspected by Kapteyn, was established by Innes in 1901, and further defined by Roberts.[1] It has a period of $1^d\ 20\frac{1}{2}^h$; and the light-curve (Fig. 18, No. 3) intimates the occurrence, within that span, of an abortive, as well as of a sharply pronounced eclipse. A bright and a dusky star are thus perceived to be combined in this system. Each time that they come into conjunction there is a noticeable diminution of their joint light, but the effect is conspicuous only when the lustrous body passes behind its companion.

The curve of R Aræ (No. 2) includes no secondary drop. This shows the occulting globe to be sensibly obscure. Its concealment makes no difference in the sum-total of light.

S Velorum is one of many variables detected during the construction of the Cape Photographic Durchmusterung. Mr. C. Ray Woods first noted its fluctuations in 1894,[2] and Mr. Roberts ably investigated the nature of the system in which they arise.[3] A large semi-obscure star has, it appears, a comparatively small but much brighter companion revolving in $5^d\ 22\frac{1}{2}^h$. The obscuration represented by the profound gap in the curve (Fig. 18, No. 1) is due to the transit of the dim primary over its lucent satellite, which it completely hides during a minimum lasting $6^h\ 35^m$. For so long, in short, one star is, to our vision, substituted for another. This ingenious theory, however, is hampered by the anomalous consequence that the lustrous globe must, on its showing, be twenty times denser than its obscure attendant. Its final acceptance depends upon the verdict of the spectroscope.

We have insensibly passed on from Geminid stars to the consideration of Algol variables. These, which form Pickering's Class V., are of very peculiar interest from the amount of precise knowledge which they place at our disposal. Their characters, accordingly, invite close scrutiny and minute comparison with theory. Variability is in them by short accesses, and consists always in a temporary loss of light. They undergo, in fact, what are now known to be real eclipses at

[1] *Astr. Journ.* No. 508. [2] *Monthly Notices*, vol. lv. p. 211.
[3] *Astr. Journ.* No. 327; *Astroph. Journ.* vols. iv. p. 270; x. p. 314.

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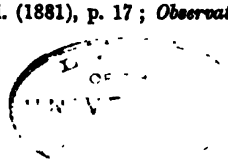
stated intervals, while shining, for the most part, as steadily as ordinary stars. Their detection is for this reason so difficult that, until the era of photographic discovery began, acquaintance with them was casual and scanty. Now, however, about thirty figure in our catalogues, the designations of which are given in Table III. of our Appendix; and the list excludes such dubious instances as S Antliae, in which the occurrence of eclipses is still *sub judice*.

The eponym of the class is curiously exact in its changes, which have been long and accurately observed. Their extraordinary character was determined, and an explanation of them by interpositions of a dark satellite suggested by Goodricke in 1783, since when some 15,600 minima have occurred in a manner perfectly consistent with the hypothesis. It became then of great interest to test its absolute truth, and the first means of doing so were afforded by Professor Pickering's strict inquiry into the conditions of the supposed recurring eclipse.[1] They proved to be all but perfectly complied with. Outside of the twelve hours during which the "Demon-star" parts with and regains two-thirds of its light, it displays the required uniform lustre. The oscillation is the same, or very nearly the same, in duration and extent now that it was fifty years ago, and that it probably will be fifty years hence. The precision of its performance seemed to correspond far better with the results of geometrical rule and measure than with those of the complex interaction of physical causes; and the spectroscope testified in the same sense by showing the surviving light at minimum to be of unchanged quality. It is dimmed, as if in large measure cut off, but betrays no symptom of intrinsic modification. These singular correspondences have not proved deceptive. The postulated eclipses actually take place.

The manner in which their genuineness has been established illustrates the singular versatility of modern methods of research. No problem in which distant light-sources are concerned seems hopelessly beyond their grasp. The received explanation of Algol's changes evidently involved the mutual revolution, in a period identical with theirs, of the eclipsed and eclipsing bodies. And since their orbits, to admit

[1] *Proc. Amer. Acad.* vol. viii. (1881), p. 17; *Observatory*, vol. iv. p. 116.



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of a transit of the satellite over the primary, should lie almost edgewise to our sight, practically the whole of their velocity should, in the course of each revolution, be directed alternately straight away from and straight towards the earth. Here, accordingly, spectroscopic measures, recommended by Professor Pickering,[1] were clearly applicable; and their photographic execution by Professor Vogel in 1888-89[2] eventuated in one of the most remarkable verifications of theory on record.

Before each minimum Algol was found to be moving away from the sun (independently of a continuous translation *towards* him of $2\frac{1}{3}$ miles a second) at the rate of $26\frac{1}{3}$ English miles per second; after each minimum, to be approaching with an equal speed; while at intermediate times the imprinted lines, by resuming their normal positions in the spectrum, proved the star to be then moving perpendicularly to the visual ray. Multiplying this velocity (of $26\frac{1}{3}$ miles) by the number of seconds in Algol's period (247,735) we get an orbital circumference corresponding to a diameter of (in round numbers) two million miles. Moreover, since the proportionate dimensions of the bright and dark bodies are shown by the amount of obscuration of one by the other to be very nearly as 100 to 83, their relative masses would also be known, if we could be sure that they are of the same mean density. The assumption as regards a mass shining with great brilliancy and one almost totally dark is certainly a hazardous one, but it receives some warrant from the example of the sun and Jupiter. By its aid Professor Vogel arrived at the following provisional data for the system of Algol:—

Diameter of Algol . .	1,061,000 English miles.
„ satellite . .	834,300 „
Distance from centre to centre .	3,230,000 „
Orbital velocity of Algol . .	26·3 miles per sec.
„ „ satellite .	55·4 „
Mass of Algol . . .	$\frac{4}{3}$ solar mass.
„ satellite . . .	$\frac{2}{3}$ „

In the accompanying diagram C marks the centre of gravity round which both stars revolve with velocities inversely proportional to their masses. Thus, Algol travels in

[1] *Proc. Amer. Acad.* vol. viii. p. 34.
[2] *Astr. Nach.* No. 2947.

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an orbit of only half the compass of that of its companion, because possessed of twice its attractive force. It is easy to see, too, that the duration of the eclipse compared with the length of the period gives the relation between the diameter of the occulted body and the diameter of the orbit of the occulting body, so that the absolute dimensions of one becoming known, those of the other follow.

The density alike of Algol and of its satellite must be less than a quarter that of the sun, or 0·38 that of water. They are both then presumably gaseous. Some slight dissymmetry in the phase-curve, formerly perceived or imagined, and set down by Dr. Wilsing[1] to the account of ellipticity in the path pursued, has not of late been verified.[2] Although the interval between Algol's successive eclipses shortened by eight seconds between 1790 and 1880, when the process became reversed, it does not follow that the star's orbital period is subject to alteration. Dr. Chandler holds the inequality to be merely apparent —to represent the time occupied by light in crossing a wide ellipse described by the occulting pair round a supposed dark primary.[3] The visibility of the phases would, if that were so, be alternately accelerated and delayed according as the body undergoing them was on the hither or the farther side of its great orbit. Nor is it impossible that Chandler's theory may ultimately be directly verified by the micrometrical measurement of undulations in the proper movement of Algol[4] corresponding to its suggested spacious circuitings in a period of about 118 years. M. Tisserand, on the other hand, rejecting the idea of a triple system, explained the deviations of the eclipses from their normal epochs by a progression of the line of apsides due to the presumed spheroidal shape of the

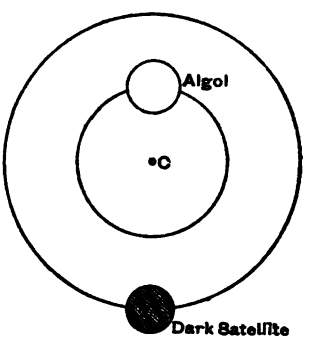

FIG. 20.—Algol during an Eclipse.

[1] *Astr. Nach.* No. 2960.

[2] G. Müller, *Ibid.* No. 3732; H. C. Vogel, *V. J. S. Astr. Ges.* Bd. xxxvi. p. 140.

[3] *Astr. Journ.* Nos. 255-56, 509.

[4] Boss, *ibid.* No. 343.

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contiguous globes.[1] This would necessarily bring about a cyclical fluctuation in the eclipse-period. Yet here, too, confirmation is still lacking; the implied eccentricity of the star's orbit not being spectroscopically apparent.

It needs no argument to prove that the eclipse-theory of the variable in the head of Medusa must apply to all other members of the same sharply characterised class. Many of them, however, present anomalies which are the more deserving of careful study that they may one day throw an important light on the circumstances under which combinations of the indicated kind exist.

The light-change of S Cancri was discovered by Mr. Hind in 1848, and its peculiar nature ascertained by Argelander in 1852.[2] The star remains steady during thirteen-fourteenths of its period, then declines, in eight hours and a half, to less than one quarter of its usual brightness, which it regains in the course of thirteen hours more. The process of recovery, besides being abnormally slow, is interrupted soon after it has begun by a marked pause,[3] represented graphically from Schönfeld's observations in Fig. 21. The compass of this star's change appears to be by no means invariable. On April 14, 1882, Schmidt observed at Athens a minimum nearly two magnitudes fainter than any he had seen before. During one hour the star remained sunken nearly to the *twelfth* magnitude.[4] The period of S Cancri is subject to a perturbation with a range of about forty minutes, and embracing rather more than three hundred minima.[5]

Inequalities of this kind, which in Algol sum up to a few seconds in a century, and grow to many minutes in S Cancri, are in λ Tauri counted by hours.[6] Their method and cause have still to be unravelled. The companion of λ Tauri is not, like that of Algol, entirely obscure. M. Bélopolsky spectrographically resolved the variable, in 1897,[7] into an unequally bright pair, revolving in $3^d\ 23^h$, the period of light-

[1] *Comptes Rendus*, t. cxx. p. 125.
[2] *Astr. Nach.* Nos. 796, 804, 806.
[3] *Vierteljahrsschrift Astr. Ges.* Bd. ix. p. 230.
[4] *Astr. Nach.* No. 2491.
[5] Argelander, *Bonner Beob.* Bd. viii. p. 397; Schönfeld, *Sirius*, Bd. x. p. 68.
[6] Schönfeld, *Jahresbericht*, Mannheim, Bd. xl. p. 76.
[7] *Astr. Nach.* No. 3474.

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change. A secondary minimum, detected by M. Plassmann in 1890,[1] corresponds to the occultation of Bélopolsky's faint component, as the chief minimum does to that of its primary. The disparate coupled eclipses of R^2 Velorum (Fig. 18, No. 3) are thus repeated by λ Tauri.

The variations of U Cephei, first recognised by M. Ceraski at Moscow, June 23, 1880, are unusually rapid and extensive. In four and a half hours the star is reduced to about one-ninth its ordinary lustre, losing light, at one stage of its decline, at the astonishing rate of more than one magnitude an hour! The obscurity lasts an hour and a half, but not

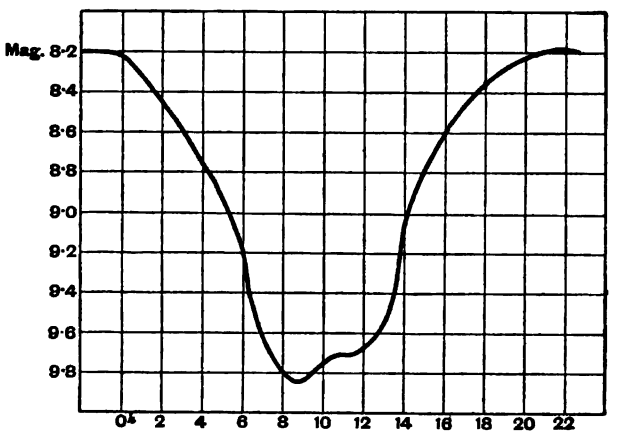

Fig. 21.—Minimum of S Cancri.

with entire uniformity.[2] The lowest point is touched at first,[3] and a pause in the ascent, like that inflecting the light-curve of S Cancri (see Fig. 21), is indicated. Mr. Yendell, on the other hand, pronounces the light-curve to be symmetrical, and regards the minima as annular eclipses of two hours' duration.[4] Some complicated irregularities in the period of U Cephei have been ascertained by Dr. Chandler, and M. Plassmann observed the minimum of April 27, 1902, to occur $2^h\ 27^m$ later than the calculated time.[5]

The period of Y Cygni, added to the list of Algol variables

[1] Plassmann, *Die veränderlichen Sterne*, p. 42; *Journ. Brit. Astr. Ass.* vol. i. pp. 137, 255.
[2] Bohlin, *Astr. Nach.* No. 3762.
[3] Chandler, *Astr. Journ.* No. 199, p. 53.
[4] *Astr. Journ.* No. 551.
[5] *Astr. Nach.* No. 3796.

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by Dr. Chandler, December 9, 1886, averages about a day and a half,[1] but fluctuates to an extent unparalleled in this kind of star. The retardation of its phases between 1887 and 1888 amounted to *seven hours*, totally disconcerting prediction, and the period soon afterwards set about shortening as rapidly as it had lengthened before.[2] The actual change does not exceed half a second at each of the returns, but these are so numerous that the accumulating errors sum up in a short time to a startling aggregate. They have been successfully rationalised by M. Dunér[3] on the principle applied by Tisserand to the irregularities of Algol. The phases of Y Cygni, however, are duplicated, the conjoined stars being twins in size and splendour. Hence they take it in turn to be eclipsed, and revolve in twice the mean interval between their conjunctions. Their orbit has an eccentricity of 0·145; its major axis completes a gyration in forty-one years; and its varying position with regard to the line of sight determines the amount by which any individual eclipse falls behind or anticipates its due epoch. The system of Z Herculis, although composed of dissimilar stars, exhibits analogous symptoms of perturbation to those presented by Y Cygni.[4]

Stellar eclipses, it need hardly be said, are purely relative phenomena. Their occurrence depends upon the situation of the observer. But the chance of their being visible from a distant point augments very greatly with the closeness of the revolving stars; for which reason, and also because the phases recur more frequently when the orbit is narrow, Algol variables with periods exceeding four or five days are of extreme rarity. Until 1902, S Cancri was the only such instance known. In that year, however, Mrs. Fleming discovered in UZ Cygni a star with an eclipse-interval of 31·3 days,[5] or more than thrice as long as that of S Cancri. Each of its minima lasts two days, and the loss of light amounts to two magnitudes. Secondary obscurations, symmetrically dividing the period, have lately been detected by Hartwig,[6]

[1] Chandler, *Astr. Journ.* Nos. 163, 185. [2] *Ibid.* No. 204.

[3] *Astr. Nach.* No. 3467; *Astroph. Journ.* vol. xi. p. 175; *Knowledge*, vols. xv. p. 87; xvi. p. 166.

[4] Dunér, *Astr. Journ.* Nos. 374, 384, 422; *Astroph. Journ.* vol. i. p. 285; Yendell, *Astr. Journ.* Nos. 328, 366.

[5] *Harvard Circular*, No. 65. [6] *Astr. Nach.* No. 3944.

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and occasion some perplexity by their apparent recalcitrance to the hypothesis of a double eclipse. Their observer, in fact, discards that hypothesis, and suggests instead the view that UZ Cygni is a "pear-shaped" body or "apioid," rotating in what was taken for the period of its systemic circulation.

Eclipsing stars are remarkably tenuous bodies. The comparison of the duration of their transits with the periods of their revolution supplies means for deducing a limiting value for their densities,[1] and it was fixed by Mr. H. N. Russell in 1899,[2] from an average of seventeen stars, at one-fourth that of the sun. Mr. A. W. Roberts, working independently on the same lines, found the mean consistency of four southern Algol-pairs to be about one-eighth the solar.[3] The range of variety in this respect among such stars is evidently very considerable; but all appear to be less compact than our sun. The circumstance is also noteworthy that eclipsing stars agree in showing a Sirian or a helium spectrum. No exception to the rule at least has yet come to our notice. The solar type, on the other hand, predominates among ordinary short-period variables. Variable stars of all classes are probably at enormous distances—even on the celestial scale—from the earth. There is no sign that any of them are included among the stars in our comparative vicinity. One of the best means of forming a rough judgment on this point is by the amount of apparent motion; and variables remain in general nearly fixed in the sky. Mira, perhaps the most mobile, shifts its position indeed to the not wholly inconsiderable extent of twenty-five seconds of arc in a century, but measures for parallax would be much embarrassed by its changes of magnitude, and have not yet been attempted. Dr. Chase's determination of a distance for Algol[4] about ten times that of Sirius is the only piece of direct information yet obtained as to the remoteness of variable stars.

Their distribution over the sphere presents some noticeable peculiarities. Contrary to what might have been expected, short-period variables, although on the whole much brighter objects than those of long period, tend much more decidedly to concentration in the Milky Way, while the preference for

[1] Maxwell Hall, *Observatory*, vol. ix. p. 224.
[2] *Astroph. Journ.* vol. x. p. 315. [3] *Ibid.* p. 308. [4] *Astr. Journ.* No. 318.

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its plane belongs chiefly to faint stars among those not variable. In Algol stars it is less strong than in periodical stars of Pickering's fourth class. These lie, for the most part, along a great circle nearly, but not quite coincident with the medial line of the galaxy.[1] It is remarkable that their condensation-level (as is shown by its being projected into a *great* circle) passes through the sun. Within the zone itself, there is an evident disposition towards clustering. Where the Milky Way divides in Cygnus, the variables follow its southern branch, and they are thickly sown over the whole sky-region from Lyra to Sagittarius.[2] Indications abound that the conditions of variability, and even of particular kinds of variability, are localised in space. Thus, in Sagittarius no less than four stars fluctuate in periods of six to seven days, and many others are subject to slower or undetermined vicissitudes. Two adjacent stars in the Southern Triangle vary in unusually short periods. A small region near η Carinæ includes six stars changeable in brightness.[3] Dr. Max Wolf has lately published[4] a list of thirty-six variables grouped round δ Aquilæ. The Orion nebula and the Magellanic Clouds are veritable nests of fluctuating light-points. The new star which appeared in Scorpio in 1860 marked the centre of a group of nine or ten objects, all widely variable irregularly or in long periods. Five stars of a similar nature, including two virtually extinct Novæ, are collected in a small section of Ophiuchus, and in general the sites of temporary stellar apparitions are more or less closely dotted round with variables. There is reason to suppose that the circumstances favouring instability of light do not exist anywhere in the neighbourhood of the sun.

[1] The northern pole of this circle, according to Pickering, is situated in R.A. 13h., Dec. +20°. That of the Milky Way is in R.A. 12h 40m., Dec. +28°.

[2] Chandler, *Astr. Journ.* No. 193; Plassmann, *Die veränderlichen Sterne*, p. 85.

[3] Gore, *Knowledge*, vol. xiv. p. 193. [4] *Astr. Nach.* No. 4005.

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CHAPTER X

THE COLOURS OF THE STARS

THE stars differ obviously in colour. Three or four among the brightest strike the eye by their ardent glow, others are tinged with yellow, and the white light of several has a bluish gleam like that of polished steel. Reddish tints are, however, in the few cases in which they affect lucid stars, the most noticeable, and were the only ones remarked by the ancients.

Ptolemy designates as "fiery red" (*ὑπόκιρροι*) the following six stars: Aldebaran, Arcturus, Betelgeux, Antares, Pollux, and—*mirabile dictu*—Sirius! all the rest being indiscriminately classed as "yellow" (*ξάνθοι*). Now Pollux at present, though by no means red, is at least yellowish, but Sirius is undeniably white with a cast of blue. A marked change in its colour since the Alexandrian epoch thus appears all but certain, the more so that Seneca makes express mention of the dog-star as being "redder than Mars."[1] Horace has "rubra Canicula" as typical of the heat of summer,[2] and Cicero, in his translation of Aratus, speaks of its "ruddy light." Significant, too, in the same sense was the custom described by the grammarian Festus of sacrificing red dogs at the feast of the Floralia for the purpose of placating in the interests of the approaching harvest, the formidable and inimical dog-star. The whole subject has been learnedly discussed by Dr. See,[3] who may be said to have fairly established his contention that the present white lustre of Sirius does not date back more than a thousand or 1200 years. In the tenth century

[1] *Quæst. Nat.* I. i. [2] Sat. ii. 5, 39.
[3] *Astr. and Astrophysics*, vol. xi. p. 269, etc.

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the star was assuredly no longer red. Al Sûfi, a genuine observer, pointedly omits it from the list of those exceptionally coloured, while adding to it "Cor Hydræ" and Algol[1]—Algol, now a silvery orb, if there be one in the sky; yet it is worth recording that Schmidt noticed the Perseus variable as yellowish red in 1841, although he never in later years saw it otherwise than white.[2]

The same observer was amazed, March 21, 1852, to perceive Arcturus without a trace of the strong colour familiar to him in it during eleven previous years. In comparison with its paleness, Capella seemed bright yellow, Mars and Betelgeux glowed almost like fire.[3] It was some years before the star resumed its original hue, and the reality of the change, admitted by Argelander, was certified by the observations of Kaiser at Leyden.[4]

The periodical variations in colour of *a* Ursæ Majoris, the "Pointer" next the pole, announced by Klein in 1867,[5] were long disbelieved in. Nevertheless, a series of observations with Zöllner's polarising colorimeter, executed in 1881 by M. Kövesligethy, of the O Gyalla observatory in Hungary, gave evidence of alternating fluctuations between red and yellow in a period of 54½ days;[6] and essentially confirmatory results have recently been obtained by MM. Lau and Wirtz.[7]

The colours of the stars visible to the naked eye are faint and pale compared with those disclosed by the telescope. The real gems of the sky are found low down in the scale of brightness. To some extent this is only what might be expected. Intense tints result from strong selective absorption in the atmospheres of the stars they distinguish, and strong absorption implies large loss of light. Stars shine with the rays that have survived transmission through the glowing vapours in their neighbourhood, and the more nearly those rays are limited to one particular part of the

[1] Schjellerup, *Description des Étoiles Fixes*, p. 25.
[2] *Astr. Nach.* No. 1099.
[3] *Ibid.* No. 999.
[4] *De Sterrenhemel verklaart*, Pt. i. p. 597.
[5] *Astr. Nach.* Nos. 1663, 2111.
[6] *Sirius*, Bd. xiv. p. 253.
[7] *Jahrbuch der Astronomie*, Bd. xiv. p. 125.

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spectrum, the purer and clearer the resulting tint will be. A true prismatic hue could accordingly be produced only through a vast reduction of brightness; but true prismatic hues do not exist among the stars,[1] the colours of which are always more or less copiously diluted with white light.

The science of star-colours has hitherto made little progress. Attempts to set up a standard chromatic scale have not been successful,[2] and instrumental devices for ensuring just and equable judgments may sometimes induce larger errors than they avert.[3] Simple visual estimations, on the other hand, must be treated with great reserve, since "personal equation" in this matter often assumes enormous proportions. The extreme of colour-blindness is reached by comparatively few, but endless minor individualities of perception vitiate the greater part of an accumulated mass of evidence which might otherwise justify inferences of real change. From the complex bundle of rays forming the image of a star, each retina picks out and accentuates those to which it is most highly sensitive, precluding the possibility of agreement as to delicate tints between many different observers. With both the Herschels, for instance, the equilibrium of colour was shifted towards the red end of the spectrum. Struve's assistant, Knorre, saw all stars indiscriminately white; Admiral Smyth, on the contrary, discriminated between shades of colour altogether inappreciable to most of those who have profited by his "Cycle of Celestial Objects."

Even of the same observer the impressions do not always agree. Fatigue and advancing years modify the colour-sense; and M. Safarik stated that stars invariably appeared redder to his left than to his right eye.[4] Atmospheric conditions, too, are powerfully operative. Misty air blots out faint tints and alters strong ones, azure visibly turning green through its influence. Height above the horizon is another circumstance to be taken into account before any useful comparisons can be made, while instrumental causes tend further

[1] Struve, *Mensuræ Micrometricæ*, p. lxxxvi.

[2] See the system proposed by Franks, *Monthly Notices*, vol. xlvii. p. 269.

[3] See the results given by Kövesligethy, *Ueber eine neue Methode der Farbenbestimmung der Sterne*, Halle, 1887.

[4] *Vierteljahrsschrift Astr. Ges.* Jahrg. xiv. p. 378.

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to perplex their upshot. Large apertures help of themselves to bring out colour,[1] especially in small stars, but the colour-correction of great refractors is always imperfect, and the outstanding blue fringe usually conspicuous in them must by contrast give a reddish cast to the image.[2] Reflectors produce a similar effect through absorption of many of the higher rays by the silvered glass or speculum-metal forming their mirrors. And since with high magnification all hues merge, or tend to merge, into yellow, only medium powers should be used in colour observations.

In this department then, discrepant statements by no means necessarily imply actual variation. The former abound; instances of the latter are met with, but can only be admitted with extreme caution.

The study of star-colours divides naturally into two branches—one concerned with isolated, the other with compound objects. Inquiries in the first case are simplified by the curious and unexplained fact that single stars are never markedly tinged except with red or yellow. Vega makes the nearest approach in the northern hemisphere to an independently blue star; γ Toucanæ, α Eridani, and ϵ Pavonis are the "pale sapphires" of the southern sky. But they are very pale indeed—so pale as to produce no definite impression of colour upon ordinary eyes. Nor is the "emerald" tinge of β Libræ much more decided. We have accordingly to deal just at present only with "red stars."

The earliest list of thirty-three of them was drawn up by Lalande in 1805.[3] "Ces étoiles," von Zach remarked in republishing it in 1822, "annoncent toujours quelque chose de particulier; or toute particularité mérite d'être observée."[4] We have to a great extent got rid of the notion which presented itself to John Michell in 1767,[5] that what they "announce" is the impending extinction of their own fires; but their peculiarities have become, on that very account, all the more worthy of attention. Red stars are commonly variable both in light and colour; the display of colonnaded

[1] Struve, *Mens. Microm.* p. lxxxvi. Mr. Franks held the opposite opinion.
[2] Webb, *Student*, vol. v. p. 487.
[3] *Connoissance des Tems pour l'an* 1806.
[4] *Corresp. Astr.* t. vii. p. 296.
[5] *Phil. Trans.* vol. lvii. p. 238.

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and zoned spectra belongs exclusively to them; and they are frequently characterised by atmospheric incandescence as well as by atmospheric instability. Few of them can be watched long and attentively without being caught in some singular phase of change.

Their systematic study began with the publication in 1866 of Schjellerup's Catalogue of 280 red stars;[1] ten years later, Mr. Birmingham of Tuam completed a similar work comprising 658 entries,[2] and Mr. Chambers laid before the Royal Astronomical Society, April 6, 1887, a catalogue founded on his personal observations during seventeen years.[3] Of 711 nominally red stars in both hemispheres he had examined 589, being virtually all those visible in England, with the result of finding the colour of most exaggerated. "Orange" was to his eye the tint prevailing among them; true "reds" were scarce; of stars meriting to be qualified as "carmine" or "ruby" he had not met above a dozen.

More recent works of the kind have their value enhanced by spectroscopic indications. Such were added in 1888 to Mr. Espin's edition of Birmingham's Red Stars, augmented to the number of 1472, and to Krüger's *Catalog der Färbigen Sterne* (Kiel, 1893), which includes 2153 more or less deeply-tinted objects.

None present saturated colours. The perfect crimson of a solar prominence cannot be matched among the stars. Their hues result from atmospheric action, and stellar atmospheres are only partially effective in sifting the prismatic rays. Red stars are none the less striking telescopic objects. Their light, even in the less distinguished specimens, has a lurid glow which at once marks them out from ordinary stars, and those of deeper tints shine with an ardour recalling the wrathful intensity of a stormy sunset. The contrast between a red and a white star in the same field of view is sometimes most vivid and beautiful. Thus, in the southern constellation Grus, π^1 and π^2 show like little burnished discs of copper and silver respectively, seen under strong illumination.

[1] *Astr. Nach.* No. 1591; reprinted with numerous additions in *Vierteljahrsschrift Astr. Ges.* Jahrg. ix. p. 252.

[2] *Memoirs R. Irish Acad.* vol. xxvi. p. 249.

[3] *Monthly Notices*, vol. xlvii. p. 348.

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Among conspicuous stars, Antares, in the heart of the Scorpion, is the ruddiest, Betelgeux comes next; while Aldebaran and Arcturus have figured immemorially in the short list of visible fiery objects, to which Al Sûfi (as already mentioned) added α Hydræ, and Father Noël γ Crucis. But their colours are mere pale shades compared with those instrumentally brought into notice. "Hind's crimson star," otherwise known as R Leporis, appeared to its discoverer in 1845 like "a drop of blood on a black field." As with most other variables, however, increase of light brings with it a paling of colour. Near maximum, intense redness gives place, partly through a well-known physiological effect,[1] to a coppery hue. Its spectrum is of the fourth type, with particularly strong absorption of the blue rays, a very small proportion of which penetrate its dense veil of carbonaceous vapours.

A similar object, now known as V Hydræ, is No. 16 of Lalande's, No. 136 of Schjellerup's Red Stars, and was recorded by Dr. Copeland at Dunsink, March 22, 1876, as "brown red," and of 7·2 magnitude.[2] But three years later, Dr. Dreyer found it risen to the sixth magnitude, and of a "most magnificent copper red," while Birmingham observed it in 1874 as of the eighth, Dunér in 1884, as faded to 9·5 magnitude. Its fluctuations of light are comprised in a nominal period of 575 days.

Close to one of the gems of the Southern Cross, an eighth-magnitude star was described by Sir John Herschel to be of "the fullest and deepest maroon red, the most intense blood-red of any star I have seen. It is like a drop of blood when contrasted with the whiteness of β Crucis."[3] Among other southern stars remarkable for colour are R Sculptoris, no less "intensely scarlet" now than when Gould saw it at Cordoba, R Doradûs, glowing like a live coal out of the darkness of space, and L_2 Puppis, all of them noted variables.

In the northern hemisphere, V Cygni bears the palm for depth of tint, especially as its light diminishes; and not far inferior to it are R Cassiopeiæ, R Leonis, R Crateris, and Mira, with U Cygni and U Cassiopeiæ, both splendidly set off

[1] Osthoff, *Astr. Nach.* No. 3940.
[2] *Dunsink Observations*, vol. iv. p. 55.
[3] *Cape Observations*, p. 448.

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by the vicinity of blue attendants. Crimson, indeed, verges, in these and other periodical stars, more and more towards orange in their brightening phases, yet they remain pretty constantly "red." A few cases of complete if temporary change of colour have, however, been recorded. Thus, a seventh-magnitude star in the Lynx (90 Schjellerup) noted by Struve as "rubra," by Secchi as "bella gialla," seemed to Birmingham, January 13, 1874, blue or bluish white, a confirmatory and nearly contemporaneous observation being made at Greenwich.[1] A star of $8\frac{1}{2}$ magnitude (148 Schjellerup) called "scarlet" by Lord Rosse in 1861, "dark red" by d'Arrest, December 8, 1866, showed "no colour" to Birmingham, May 8, 1874. Dunér found it, nevertheless, of a deep orange red in 1884, and it is characterised by a fine colonnaded spectrum. Again, Schjellerup was struck with the redness of a star in Aquila[2] in 1863, which, after an interval of ten years, struck Birmingham as actually *blue*; and similarly a bluish-white object occupied the place, November 14, 1850, of a star in Taurus (Schjellerup, 64 *b*) marked "very red" by Hind, September 3, 1848,[3] which Dreyer perceived as once more red in January 1879, but Espin as white with a continuous spectrum, January 10, 1888. One further instance may be mentioned. A fifth-magnitude star in Argo, known as *r* Velorum,[4] was notoriously red during Gould's stay at Cordoba. But it seemed leaden white to the present writer in the autumn of 1888, and was observed by Mr. Tebbutt in March 1891 as barely tinged with red, though the tinge became more decided on substituting an 8-inch for a $4\frac{1}{2}$-inch equatoreal. The spectrum of *r* Velorum closely resembles that of Aldebaran.

The changes of colour visible in temporary stars have generally been in an opposite direction to those of ordinary variables. Their sanguine tints faded, instead of deepening with the decline of their light. Thus, Tycho's star, though it passed through an intermediate stage of redness, was of a leaden white when it disappeared. T Coronæ ran nearly the

[1] *Memoirs R. Irish Acad.* vol. xxvi. p. 269.

[2] No. 6803 of the *Copenhagen Catalogue;* No. 214 of *Schjellerup's Red Stars.*

[3] *Monthly Notices*, vol. xi. p. 46.

[4] The place of the star for 1900 is R.A. $10^h\ 18^m{\cdot}1$, D-41° 9′.

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same course. Nova Ophiuchi (1848) and Nova Andromedæ were ruddy at first, colourless later. Nova Cygni from orange turned bluish. The colour changes of Nova Persei were not the least curious part of its history. Purely white at its outburst, February 22, 1901, it rapidly flushed to a deep red, which lightened to orange during the spasms of intermittent brightening observed in March and April. The steady decline of the star was nevertheless accompanied by a progressive loss of colour, until on February 5, 1902, it showed to Professor Barnard greenish-white, like Neptune.[1] Its nebular spectrum was by that time fully developed; but its antecedent redness was unaccounted for by any marked absorption in the blue or green. Nova Geminorum similarly glowed vividly at first, but blanched with the waning of its sudden access of light. In its case, however, the predominance of red hydrogen in its emissions explained the initial ruddiness of its hue. Professor Barnard[2] was able, by suitably drawing out the eye-piece of the Yerkes 40-inch refractor, to form on the C-line a crimson image of the star as purely tinted as a solar prominence. This is the only ascertained instance of the production of stellar colour by direct radiation instead of by complementary absorption.

Red stars are very unequally scattered. Certain wide tracts of the sky are nearly destitute of them; in some, they occur profusely. The Milky Way between Aquila, Lyra, and Cygnus was called by Birmingham the "Red Region";[3] yet other galactic constellations, such as Perseus and Cassiopeia, might be said, on a preliminary survey, to consist of white stars.[4]

Evidently, however, real partialities of colour-distribution must be to a great extent masked by the projection, to the eye, of objects at indefinite distances from each other upon the same portion of the sphere. Hence extensive local collections of similar stars may be so confused with overlying and underlying aggregations as to be completely unrecognisable. Smaller groupings are more readily detected. It is by

[1] *Monthly Notices*, vol. lxii. p. 418.

[2] *Astroph. Journ.* vol. xvii. pp. 302, 376.

[3] *Memoirs R. Irish Acad.* vol. xxvi. p. 255.

[4] Franks, *Monthly Notices*, vol. xlvi. p. 343; see also Osthoff, *Wochenschrift für Astr.* Bd. xix. (1876) p. 326.

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no accident that, in the immediate neighbourhood of one red star, others are so apt to be met with; and the "brick red" and "ruby" pairs included in Herschel's Cape list, may with confidence be assumed to be severally in some sort of physical connection. Red stars, it was remarked by the same authority, are conspicuous in many clusters both by brightness and situation; and Father Secchi was struck with the critical positions of such objects as regards spiral or radiated stellar arrangements in the Milky Way.[1]

The principle of colour by association, barely indicated in clusters, is in double stars carried out to the highest perfection. Nature is inexhaustible in her display among them of harmonies, contrasts, and delicate gradations of hue. They not only vividly sparkle in green and gold, azure and crimson, but shine in the sober radiance of fawn and olive, lilac, deep purple, and ashen grey. Chalcedony, aquamarine, chrysolite, agate, and onyx have counterparts in the heavens as well as rubies and emeralds, sards, sapphires, and topazes.

Mariotte of Dijon, a physicist, but no astronomer, was the first to speak of *blue* stars. "Les étoiles qui paraissent bleues," he wrote in 1681, "ont une lumière faible, mais pure et sans mélange d'exhalaisons."[2] But he gave no examples, and it is not easy to divine what class of objects he alluded to. The chromatic observation of double stars was really begun by Father Christian Mayer at Mannheim in 1776; although the interest of his preliminary efforts was absorbed in the splendour of Herschel's similar but vastly more extensive and assured results. He not only discovered a great number of exquisitely tinted couples, but by his success emphasised the importance of systematic attention to colour in double stars.

His example was followed by F. G. W. Struve, who in 1837 classified from this point of view 596 of the brightest known stellar pairs. The upshot was to prove agreement in colour the rule, contrast the exception.[3] Just half, or 295 of the objects examined were uniformly white; 118 had both components yellow or reddish with slight differences of

[1] *Atti dei Nuovi Lincei*, t. vii. p. 72.
[2] *Oeuvres*, t. i. p. 287.
[3] *Étoiles Doubles*, pp. 33-34; *Mensuræ Microm.* p. lxxxii.

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intensity; sixty-three were tinctured with blue. The instances of genuine contrast numbered 120, and in *all* of these the small star was called blue. The rule is, moreover, without exception, that no primary member of a dissimilarly tinted pair is blue.

The reality of chromatic contrasts in double stars was established by the persistence of colour in satellites during the obliteration of their primaries by an interposed wire or bar; and besides, as Struve remarked, optically produced hues should be invariably complementary, which is far from being the case in stars. A curious proof of this independence was afforded by a double occultation of Antares and its companion observed by Dawes in 1856. The small star, emerging first from behind the moon, seemed as perfectly green viewed thus alone as when half lost in the glare of the great red star it is attached to.[1] The same phenomenon was reobserved in 1878.

The connection between inequality of brightness and unlikeness of tint in coupled stars did not escape Struve's notice.[2] He found a mean difference of less than half a magnitude between the exactly similar members of 375 pairs, of over one magnitude for 101 stars showing varied shades of the same colour, and of nearly two magnitudes in 120 cases of contrasted tints. Professor Holden, taking account of physical pairs only, reached, in 1880, an analogous result.[3] Where there was identity of colour the average difference of lustre proved to be only half a magnitude, where there was diversity the luminous inequality mounted to two and a half magnitudes. One hundred and twenty-two of the stars considered belonged to the first class, forty to the second. Now markedly unequal are generally wide pairs,[4] so that disparity of hue is seen to prevail in systems formed by a large star and a comparatively small and remote companion; while genuine twin suns, of not very different radiative power, and of similar radiative quality, circulate as a rule rapidly and closely

[1] *Monthly Notices*, vol. xvi. p. 143; Niesten, *Ciel et Terre*, t. ii. p. 96; Webb, *Cel. Objects*, p. 386.

[2] *Mens. Microm.* p. lxxxii.

[3] *Amer. Journ. of Science*, vol. xix. p. 467.

[4] Doberck, *Astr. Nach.* No. 2278. The scarcity of small, close companions to bright stars may be partly due to the difficulty of discovering them.

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round their common centre of gravity. Why this is so we cannot tell; the bare fact is before us.

Some beautifully coloured stars are, nevertheless, ascertained to be in mutual revolution. The yellow and rose-red components of η Cassiopeiæ finish their circuit in about two hundred years; those of ϵ Boötis, chrome yellow and sea-water blue, in probably upwards of twelve hundred; ξ Boötis and π Cephei, orange and purple, o Cephei and τ Cygni, golden and azure pairs, are all in swifter or slower orbital movement. A good many richly-tinted stars, on the other hand, appear stationary, doubtless because their distances apart are so considerable as to make their revolutions inordinately slow. Thus the emerald-green companion of α Herculis has preserved, during a century, an invariable position with regard to the ruddy star it depends upon, and Antares forms with its sea-green satellite a somewhat similar and equally rigid combination. The fixed pair β Cygni (Albireo) shining with "yellow topaz" and "aquacœlestis blue" light, presents perhaps the most lovely effect of colour in the heavens, nearly matched, however, by the variable δ Cephei and its cœrulean companion. Among numerous other examples of contrasted or harmonising tints in double stars may be mentioned γ Andromedæ, orange and green; γ Delphini, yellow and pale emerald; η Persei, golden and azure; 24 Comæ Berenices, orange and lilac; 12 Canum Venaticorum, pale yellow and fawn; ν Serpentis, sea-green and lilac; a pair in Cassiopeia (Σ 163), copper colour and blue; 17 Virginis, light rose and dusky red; o Draconis, orange and emerald. A few red and green pairs seem abnormal through the near approach to equality in the magnitudes of the components. One such was observed by Herschel in Pisces; and Burnham noted in 1900 the reality of the contrasted tint it presents.[1] Another was discovered by Burnham himself in Pisces. But the fiery primaries are, in both cases, likely to prove variable.

Bright white stars have not unfrequently small blue ones in their vicinity. A distant companion of Regulus seems as if steeped in indigo; Rigel has an azure attendant; λ Geminorum one of an amethystine shade; 84 Ceti and 62 Eridani are made up each of a white and a lilac star; while the

[1] *Measures of Double Stars*, p. 10.

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sapphire ι Boötis is grouped closely with one, more loosely with two other subordinate blue objects.[1]

Two questions at once suggest themselves about the colours of double stars. To the first, Are they real? a decisively affirmative answer can be given; but the second, Are they permanent? cannot be disposed of with such promptitude. The subtlety of hues resulting from a highly complex set of retinal impressions renders them peculiarly liable to *subjective* variation. As evidence of *objective* variation, then, random notes of colour are of little or no use. Only the estimates of skilled observers, trained to the needful precautions, furnished with suitable instruments, above all, owning normal eyesight, are worth weighing and comparing. Under this rule of exclusiveness, the testimony requiring the admission of real change shrinks surprisingly in compass, but does not wholly disappear. Colour-variables are to be found among compound, no less than among single stars.

Owing partly to instrumental, partly to personal causes, the elder Struve perceived as purely white many stars seen by Herschel with a tinge of red or yellow. Disagreements in the opposite direction merit, then, particular attention, and they are especially marked in two cases.[2] The components of the splendid couple γ Leonis were described by Herschel in 1784 as both white, the smaller inclining slightly to pale red.[3] But Struve saw them in 1837 golden yellow and "reddish" green; Admiral Smyth "bright orange and greenish yellow"; and strongly, though unequally yellow, they still remain. Here then we have a presumption of genuine change, which, in the companion instance of γ Delphini, is raised almost to certainty. These last stars, noted by Herschel in 1779 as both perfectly white, showed golden yellow and bluish green to Struve's scrutiny. The progress of alteration may perhaps be marked by the younger Herschel's and South's record of them as white and yellowish in 1824.[4] Their dissimilar tints of orange and green now strike the eye at the first glance with the smallest telescope.[5]

[1] Flammarion, *Catalogue des Étoiles Doubles*, p. 76.

[2] *Mensuræ Microm.* p. lxxxvii.

[3] *Phil. Trans.* vol. lxxv. p. 48.

[4] *Ibid.* vol. cxiv. p. 363.

[5] Noble, *Hours with a Three-inch Telescope*, p. 111; Franks, *Journ. Brit. Astr. Ass.* vol. v. p. 457.

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Another pair famous for colour-fluctuations is 95 Herculis, composed of two equal stars of $5\frac{1}{2}$ magnitude, planted (to appearance) immovably within 6″ of each other. Familiar with them as vividly tinted objects, Professor Piazzi Smyth was astonished, on pointing his telescope towards them from the Peak of Teneriffe, July 29, 1856, to perceive them both white.[1] In the following year, nevertheless, they shone as before in "apple green and cherry red," and were so observed by Admiral Smyth, Dawes, and others. Captain Higgens[2] actually watched these colours fade and revive in 1862-63, in the course of about a year; but no trace of them has been seen of late; the stars of 95 Herculis are now of an identical palish yellow.[3] Their spectra are not identical. Dr. Vogel, in 1899, classed one as solar, the other as Sirian in type. The history of these stars goes back to 1780, when Herschel observed them as bluish white and white; J. Herschel and South called them "bluish white and reddish" in 1824; Struve, 1828-32, greenish yellow and reddish yellow, in precise agreement with Pickering's appraisement in 1878.[4] Thus the "magnificent tints of orange and green" which Secchi admired in 1855, and Piazzi Smyth missed in 1856, were of a transitory character.

In the well-known binary, 70 Ophiuchi, there has been an equally undoubted change. Except an "inclination to red" in the smaller, the elder Herschel perceived no colour in either of these stars; his son and Sir James South called them white and "livid"; yet they were recorded by Struve as of an especially intense yellow and purple, by Admiral Smyth as "pale topaz and violet." They are now both yellow, very much as they were seen by Secchi in 1855, and by Franks in 1876; the companion was, nevertheless, marked "purplish" at Harvard College in 1878, "rose-coloured" by Flammarion in 1879.

The three stars of ζ Cancri are usually yellow, but Dembowski noticed them as all white, 1854-56, the remoter component turning yellowish or olive in 1864-65.[5] This form of concordant change through various shades of primrose or

[1] Smyth, *Sidereal Chromatics*, pp. 35, 78. [2] *Ibid.* p. 80.
[3] Noble, *Op. cit.* p. 105. [4] *Harvard Annals*, vol. xi. p. 150.
[5] *Astr. Nach.* Nos. 1110, 1574.

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cowslip is not very rare among revolving stars, while the development of colour in other pairs tends towards the production of contrast. It often happens, too, that one component only varies in hue, in which case the change *always* affects the satellite star. The attendant, for example, of δ Herculis has appeared by turns ashen, "grape-red," blue, and bluish-green; that of δ Cygni was observed by Struve as grey in 1826-1833, but conspicuously red in 1836, blue by Dawes in 1839-1841, alternately red, blue, and violet by Secchi in 1856-57, grey once more by Dembowski in 1862-63, red by Engelmann in 1865, since when it has commonly seemed light blue.[1] Again, the multiple star σ Orionis includes two if not three colour-variables; the distant companion of γ Leporis changed from pale green in 1832 to garnet in 1851 and 1874, and the satellite of ν Serpentis from lilac in 1832 to "native copper" in 1851.[2]

Eye-estimates of colour do not reach below the surface; they are mere indications, which the spectroscope and the spectrograph can alone help us to interpret. But the task is delicate for the eye, and until of late, was impossible for the camera of discriminating the varieties in quality of closely adjacent light-sources. Miss Maury managed, nevertheless, to pick out on the Draper Memorial plates eighteen "composite" spectra, in which the characters were so mixed as to suggest a twofold origin;[3] and her acumen has been vindicated by the spectroscopic resolution of several of these dubious objects into swiftly-revolving, unlike couples. Exact determinations of the kind, however, were rendered possible only through Sir William Huggins's invention of a "reflecting slit," by means of which the spectra of stars no more than 2″ apart can be separately photographed.[4] Successful impressions were thus obtained from γ Leonis, Cor Caroli (12 Canum Venaticorum), and β Cygni. From previous observations of the last-mentioned pair with a visual spectroscope, he had found their complementary colours explicable (wholly or in part) by complementary absorption;[5] but this was not

[1] Engelmann, *Astr. Nach.* No. 1676.
[2] Smyth, *Sid. Chromatics*, p. 29; Webb, *Cel. Objects*, p. 389.
[3] *Harvard Annals*, vol. xxviii. p. 92.
[4] *Comptes Rendus*, Oct. 11, 1897; *Astrophys. Journ.* vol. vi. p. 324.
[5] *Phil. Trans.* vol. cliv. p. 431.

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perceptible in the more refrangible sections of their dispersed light photographed by himself and Lady Huggins in 1897.[1] The blue star yielded a Sirian, the yellow star a solar spectrum, both of perfectly normal quality. Their exceptional tints appear to be reserved for visual explanation.

Yet the improvement of methods has brought within view the realisation of the chief desiderata in stellar chromatics. These are, first, the definite correlation of the integral effect to the eye with the analytical data furnished by the prism; secondly, the recognition of some fixed mode of correspondence between spectral and colour-variations. The foundations will then have been laid of a true science of stellar chromatics.

[1] *Atlas of Stellar Spectra*, pp. 158, 163.

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CHAPTER XI

DOUBLE STARS

A DOUBLE star is one that divides into two with the help of a more or less powerful telescope. The effect is a strange, and might have appeared beforehand a most unlikely one. Yet it is of quite ordinary occurrence. Double stars are no freak of nature, but part of her settled plan; or rather, they enter systematically into the design of the Mind which is in and above nature.

The first recognised specimen of the class was ζ Ursæ Majoris, the middle "horse" of the Plough, called by the Arabs "Mizar," which Riccioli found at Bologna, in 1650, to consist of a $2\frac{1}{2}$ and a 4 magnitude star within fourteen seconds of arc of each other. Both are white, and they make a radiant display even in a very small telescope. The accident of a bright comet observed by Robert Hooke passing, on February 8, 1665, close to γ Arietis ("Mesarthim") led to his discovery of its duplex nature. The components, each of the fourth magnitude, and eight seconds apart, are perfectly alike both in light and colour. Meanwhile Huygens had, in 1656, seen θ Orionis to be triple—it disclosed itself as quadruple in 1684; α Crucis, in the southern hemisphere, was divided by some Jesuit missionaries sent by Louis XIV. to Siam in 1685, and α Centauri by Richaud at Pondicherry in 1689; making in all five double stars detected during the seventeenth century. Four more—γ Virginis, Castor, 61 Cygni, and β Cygni—were taken note of by Bradley before 1755; and in 1776, Father Christian Mayer began at Mannheim a deliberate search for stellar couples. His thirty-

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three discoveries in two years might be described as the preliminary washings from the rich lode struck a few months later by Sir William Herschel.[1]

The plentifulness of double stars was in itself an irresistible argument for their reality. That any two unconnected bright stars should be projected closely side by side upon the sphere was improbable; that such a contingency could be repeated hundreds of times was what no sane man ought to have been capable of believing. But human credulity is nowhere more conspicuous than in what it is prepared to attribute to chance; and it needed such clear evidence of mutually circling movements as Herschel was able to produce in 1803 to establish the conviction of the *physical* existence of double stars.

The fact is one at which we can never cease to wonder. It brings us face to face with a state of things entirely unfamiliar, and of which the purpose lies beyond the scope of our limited understandings. So accustomed are we to the "sole dominion" of our own great star, that the presence of *two* suns in one sphere might well at first sight appear incredible. Yet there are many things "undreamt of in our philosophy" which are nevertheless true. Every drop of stagnant water is a world of uninterpreted mysteries; what we choose to call the "order of nature" is violated at every instant, inexplicably, by our own volition; and if that order be attended by anomalies upon the earth, how much less shall we venture to prescribe its course in the heavens?

The term "double star" is obviously quite indefinite, apart from some agreement as to its meaning; and it was in fact used by early observers in a far wider sense than it is now usually considered to bear. Many of the small and remote attendants upon brighter stars recorded by the Herschels could scarcely be presumed to have any real connection with them; 32″ was fixed by Struve as the maximum interval between the components of a genuine double star, or 16″, unless both were brighter than the ninth magnitude; the younger Struve's "Pulkowa Catalogue" included no stars beyond the narrower limit, and Mr. Burnham rejects all pairs below the eighth magnitude above 5″ apart. This progressive restriction

[1] See the writer's *History of Astronomy*, p. 18, 4th ed.

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has almost necessarily accompanied the improvement of telescopes. With the powerful and perfect refractors now in use, really close pairs accumulate faster than they can continue to be observed; and the collection of the innumerable loosely yoked and ill-assorted couples they further reveal would be inane waste of time.

Already above twelve thousand double stars, in the Herschelian sense, have been registered, of which some six thousand correspond, by the closeness of their combination, to strict ideas of what a double star should be; about 1400 are separated by 2″ or less, and between 600 and 700 are visibly revolving. These last interesting cases multiply just now with especial rapidity. They are most apt to occur, as might be expected, among those stars at the smallest apparent distances from each other, and requiring accordingly the highest optical powers for their detection. Our acquaintance with most of these is so recent that their movements are only coming to be recognised as one pair after another is re-measured after a few years' interval.

The singular profusion with which stars are planted side by side with a bare *hairbreadth* of sky between, became manifest through Mr. Burnham's discoveries made at Chicago, 1871 to 1879, while he still pursued the profession of a stenographer. His thousand new pairs included 743 at an average distance of 1″·58.[1] This means that the total interval from centre to centre of these objects was just equal to the width of a human hair held thirty-six feet from the eye. About one-tenth of that distance is the minimum at which, even with the great Lick telescope, stars can be divided, but by no means the minimum at which they can separately exist. The spectroscope has demonstrated what it was logical to infer, that numberless stars which must always, either through their distance from ourselves or the closeness of their companions, remain optically single, are nevertheless compound; hence of any given star, as of a chemical "element," we can say, not that it is indivisible, but only that it has never been divided.

Such stellar pairs as are known to be in orbital movement are called "binary stars," to signify that they form real

[1] *Memoirs R. Astr. Soc.* vol. xlvii. p. 317.

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dual systems. The finest specimen of this kind in the northern heavens is Castor, or *a* Geminorum, composed of a second and a third magnitude star 5″·18 apart. They are both white with a greenish tinge, and can be divided with a very moderate telescope, so that the sight of this brilliant and suggestive object is not reserved for the inner circle of astronomers. Now it happens that Bradley observed the relative situation of these stars in 1719, and the comparison of his record with measures of the present day shows that they have shifted in the interim to the extent of 131°, or considerably more than a third of a revolution. To complete an entire one they would need at the same rate about 500 years. But they are likely to advance upon it. The most trustworthy orbit yet computed fixes their period at 347 years;[1] and although their movements have, in the past, falsified many predictions, each successive investigator is in a better position, because commanding a wider range of data than his predecessors. The limits of uncertainty as regards time of circulation shrink of themselves with every decade that goes by.

The brightest is also the widest pair of revolving stars in the sky, and a third distinction—that of being nearer to us than any other known sidereal object—accounts for the first two. In *a* Centauri are combined two stars so brilliant that the lesser, though emitting only one-third as much light as its neighbour, is still somewhat above the second rank. It is of a deeper yellow than the primary star, and must have gained considerably in lustre during the last century unless Feuillée, Lacaille, Brisbane, and Dunlop all erred egregiously in calling it of fourth magnitude.[2] Since they were observed by the Franciscan monk, Louis Feuillée, at Lima in 1709, these stars have executed nearly two and a half revolutions. They traverse in eighty-one years[3] an orbit about as much elongated as that in which Faye's comet travels round the sun, and diverge, accordingly, at "apastron" to more than thrice their "periastron" distance. They are now 22″ apart, and are separating fast, having in 1875 swept through their

[1] Doberck, *Astr. Nach.* No. 3970.
[2] See Flammarion's *Catalogue*, p. 81.
[3] T. J. J. See, *Evolution of the Stellar Systems*, p. 148.

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point of nearest approach. The "mean radius," or half the major axis of the computed ellipse, if seen square from the earth, would subtend an angle of $17''{\cdot}7$, corresponding at the star's distance of twenty-five billion miles to an actual span of (in round numbers) 2100 million miles; so that these lustrous globes are sometimes almost as close together as Saturn is to the sun, then, after two-score years, at $1\frac{1}{3}$ times the distance of Neptune. Their mass is just twice, their light about $1\frac{1}{3}$ times that of the sun.

The spectacle is beyond doubt amazing of two such bodies united thus organically into a single stately system. That it includes many other members may be taken for granted, although we may never succeed in observing them, and are unable, even in imagination, to bestow or arrange them satisfactorily. Evidently, no planetary scheme or schemes at all resembling our own can depend upon the stars of α Centauri. A Mercury or a Vulcan, at the most, might find shelter in the close vicinity of one from the disturbing power of the other, its possible inhabitants enjoying the combined or alternating radiance of a greater and a lesser sun. Comets entering these precincts must be perplexed to decide between the two potentates claiming their allegiance, and perhaps on occasions pay their court to each in turns, throwing out tails, as they do so, of a highly anomalous character. It has, however, been suggested that the clients of double stars circulate about both simultaneously, in orbits wide enough to keep them beyond the reach of dangerous perturbations from either. This is, of course, conceivable, if for many reasons unlikely; but the surmise can neither be verified nor disproved.

The stars of 61 Cygni, like those of α Centauri, share a rapid onward movement through space. They resemble them too in spectrum and colour, and are counted among our nearest stellar neighbours. Yet they are inconspicuous, one falling short of the fifth, the other of the sixth magnitude.

Although they have been under continuous scrutiny since 1753, when Bradley noted the differences in their times of transit, it is only within the last few years that the curvature of their path has become perceptible. Besides the forward movement possessed in common by the two, the smaller also

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shifts its place sensibly as regards the larger star. But for a century and upward the shifting appeared to take place along a straight line. If this had really been the case, the fact would have abolished the presumption of their binary character, and compelled the belief, which was adopted by Captain Jacob in 1858,[1] and maintained so lately as 1891 by Mr. Burnham,[2] that the stars would eventually part company and cease to have even an apparent connection. This, we can now see clearly, was a false alarm. They are really inseparable; although the circumstances of their revolution must long remain unknown. Moreover, Dr. Wilsing's announcement in 1893[3] that the motion of one or both components was disturbed by the attraction of invisible attendants, lacks confirmation.

The systems of 70 Ophiuchi and η Cassiopeiæ have much in common. The stars forming them show similar spectra and (apart from incidental variations) similar colours. They progress through space at about the same rate,[4] and both are at nearly the same distance of twenty light years from the earth. Both, too, have proved somewhat recalcitrant to computation. The orbit of 70 Ophiuchi, more especially, though one of the earliest experimented upon, can still only be regarded as approximately determined. The stars have hitherto so persistently refused to keep to their predicted places that Mädler, Jacob, and Sir John Herschel suspected disturbance by an invisible member of their system calculated by Dr. See in 1895[5] to revolve in a period of thirty-six years. The bright companion, on this view, describes in eighty-eight years an eccentric orbit with a major axis slightly less than that of Neptune, while simultaneously tracing out, in thirty-six years, "another ellipse, which in size considerably surpasses that of the planet Mars."[6] Yet its vagaries of movement are not even thus completely explicable. The mechanism of 70 Ophiuchi has still obscure springs.

The path of η Cassiopeiæ, traversed in 196 years (accord-

[1] *Edinburgh New Phil. Journ.* vol. vii. p. 107.
[2] *Astr. Nach.* No. 3047.
[3] *Sitzungsberichte*, Berlin, October 26, 1893.
[4] Sadler, *English Mechanic*, vols. xli. p. 410; xliv. p. 322.
[5] *Astr. Journ.* No. 363.
[6] T. J. J. See, *Stellar Systems*, p. 220.

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ing to Dr. See's elements), is of an ampler sweep. Its mean radius is fifty-three times that of the terrestrial, nearly twice that of Neptune's orbit. The stars, nevertheless, at their nearest approaches come within less than once and a half times the distance of Uranus from the sun, and since they together contain more than four times the solar quantity of matter, perturbations of no slight intensity would at such times affect their perhaps visionary trains of attendant bodies.

Laplace's conjecture that space might hold as many dark as bright masses has received some countenance from the phenomena of double stars. For among them are reckoned effects of the attraction of unseen upon the movements of seen bodies, while in two cases the detection of an imperfectly luminous object has, like the discovery of Neptune, ensued upon the theoretical indication of its place.

From the nature of the proper notion of Sirius, Bessel inferred in 1844 that it did not travel alone. The line traced out by it must, were it solitary, have been straight, whereas it undulated markedly and regularly once in about half a century. Revolution in that period round an obscure companion was indicated; the elements of the hypothetical Sirian system were computed by Peters and Auwers, and the precise position of the Sirian satellite was assigned by Safford in September 1861. On January 31 following, it was found just in the right spot by Alvan G. Clark, of Cambridgeport, Massachusetts.

The companion of Sirius is a dull yellow star of tenth magnitude, almost lost in the glittering radiance of its great neighbour. Their apparent distance having diminished from 10″ in 1862 to 4″ in 1890, it was then barely distinguishable to Mr. Burnham with the 36-inch Lick refractor.[1] For six years it remained wholly invisible; unseen it passed periastron in 1894; but in November 1896 re-emerged in its predicted place, and has since steadily followed the track laid down for it. The elements assigned to the pair by Dr. O. Lohse in 1904,[2] when it had performed all but 30° of an entire circuit, may accordingly be accepted as authoritative.

The system brought to our notice is a very remarkable

[1] *Astr. Nach.* No. 2884. [2] *Ibid.* No. 3955.

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one. Its chief member is a body extremely bright in proportion to its mass; its secondary member is a body abnormally massive proportionately to its light. Sirius shines like four thousand, it gravitates like two of its companions. There must hence be an enormous disparity of temperature between them, with a probably corresponding difference of mean density. Yet they are presumably of contemporaneous origin.

At the distance of Sirius (about fifty billion miles) the sun would appear as a star of the second magnitude. A collection of twenty-one suns would barely supply the emissions of that brilliant orb, the attractive energy of which is, nevertheless, little more than twice that governing the solar system. The revolutions of its satellite are completed in $50\frac{1}{3}$ years at a mean distance twenty times that of the earth from the sun, with excursions, at apastron, two hundred millions of miles further than Neptune's. Now to control motion so swift in so spacious a path, $3\frac{1}{4}$ times the solar quantum of matter must be present; of which one-third belongs to the satellite itself, constituting it a body rather more ponderous than the sun, though giving no more than $\frac{1}{1600}$ of its light. Thus the contrast between the components of this binary star could scarcely among visible objects be more pronounced. And its significance is accentuated by its essential repetition in Procyon, the lesser dog-star.

Since its motion was known to be disturbed in precisely the same way as the motion of Sirius, no doubt was entertained of its belonging to a binary combination. But the second member of that combination long evaded search, and was at last identified by Professor Schaeberle at Lick, November 13, 1896, in the modest guise of a thirteenth-magnitude star $4''{\cdot}2$ from its primary. So far, its movements tally well with the period of forty years, hypothetically attributed to them by Auwers in 1861; but indicate probably a markedly eccentric orbit instead of the nearly circular one assigned by him.[1] Schaeberle's satellite again exemplifies the strangely disparate nature of some stellar couples. It exerts three-fifths the gravitational power of the sun, while emitting no more than $\frac{1}{90,000}$ of its light. Procyon is further off from the earth than

[1] Newcomb, *The Stars*, p. 162.

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Sirius, though not in the proportion of its inferiority in magnitude. Its actual luminosity scarcely amounts to one-fifth that of the greater dog-star.

The detection of partially obscure stellar schemes goes on apace. The disturbances of motion telescopically apparent suggested analogous disturbances of motion recognisable only with the spectroscope; and the hint has proved extraordinarily fruitful. Stars like Procyon are connected by innumerable gradations with stars like Algol. This we shall learn in some detail further on.

There are other criteria besides that of visible revolution in an orbit by which physical can be distinguished from optical double stars. Since 1812, when Bessel pointed out the conclusiveness of the argument for real connection implied in the advance together of the stars of 61 Cygni,[1] "common proper motion" has been universally admitted as a proof of genuine association. Thus the lustrous pair γ Arietis has continued relatively fixed since Bradley measured it in 1755; yet its members are fellow-travellers through space, and assuredly keep mutually circling as they go, although so slowly that a century and half count almost for nothing in the majestic cycle of their revolutions. Again, the brightest star in the Southern Cross is made up of two stars of respectively 1·6 and 2·0 magnitude 5″ apart, the situations of which have not perceptibly changed since Dunlop determined them in 1826. This amounts to saying that their small proper movement is identical. And even independently of this positive test, the probabilities are enormously against the accidental close juxtaposition of two stars so brilliant and so nearly equal as those of α Crucis.

The circumstance testifies strongly to the prevalence of physical connection between stellar pairs, that the average difference of brightness between them grows steadily with their distance apart, approximately equal being usually contiguous objects. Every degree of inequality is indeed found in undoubted systems; still the chances of optical association must obviously increase vastly, even at the same distances, with increase of optical disparity.

The background of the sky is so thickly strewn with small

[1] *Monat. Correspondenz*, Bd. xxvi. p. 160.

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stars, that we cannot be surprised if some of them happen to occupy critical situations. Rather, there is ground for astonishment at finding that certain remote satellites of bright stars seem indissolubly united to them. Regulus, for example, carries with it, as it pursues its way across the sphere, a star between the eighth and ninth magnitude, discovered by Winlock at Washington to be itself closely double. The interval between the pair and its governing body amounts to nearly three minutes of arc. Castor, too, has attached to it a tenth-magnitude star at 74″; one of seventh magnitude 90″ to the south-west of *a* Crucis evidently belongs to its cortège;[1] and Aldebaran forms with a minute object at 31″ what seems to be a permanent combination resembling in its effect to the eye that of Mars with his outer satellite.[2]

Where two close stars seem fixed, relatively and absolutely, the case for their physical union must depend upon circumstantial evidence alone. But this is sometimes of cogent import. Contrast of colour, for instance, may afford grounds for a strong persuasion of real relationship. Certain tints, as blue, green, and violet, only occur among mutually associated stars. We cannot, then, suppose the association upon which they depend for their production to be merely apparent. The topaz and azure components of *β* Cygni have no appreciable motion of any kind, and they are separated by a gap of 34″, exceeding the limit of distance of real double stars as defined by Struve. Yet it is impossible to doubt that their brilliant hues are truly expressive of the systemic union from which they in some unknown way result. The same may be said of *δ* Cephei and its bright blue attendant, and of the much closer and nearly equal stars 95 Herculis, the inference being here strengthened by the concerted changes of colour recorded of them. We might be sure, too, of the dependent status of the emerald satellites of the red stars *a* Herculis and Antares, even if it were not independently proved by a community with their primaries in very slow progressive movement.

Nevertheless, some highly coloured pairs have been con-

[1] Innes, *Reference Catalogue*, p. 111 A.

[2] Burnham, *Astr. Nach.* Nos. 2189, 2875; *General Catalogue*, p. 49.

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cluded by M. Flammarion, from a careful study of their relative displacements, to be optical.[1] Among these are *o* Draconis, which might be called a subdued replica of *β* Cygni; σ^2 Piscium, golden and blue; 42 Piscium, yellow and green; a gold and purple pair in Auriga (OΣ 154); two nearly equal stars in Perseus (Σ 434) showing lovely tints of golden yellow and azure, with several besides. If these colours be inherent, it is difficult to believe that the stars distinguished by them are simply thrown together by perspective.[2] Before venturing to pronounce, however, we must wait, and let their motions develop.

The display of similar goes quite as far as the display of dissimilar colours of an unusual kind towards proving a physical union between adjacent stars. Strikingly red pairs, for instance, even when pretty widely separated, can hardly be the result of chance. Several are known, but their fixed character discourages frequent observation. Variability of light supplies another valuable indication of relationship. When common to both members of a pair, it leaves no room for doubt on the subject. We shall recur to this topic in a later chapter.

Stars with ascertained proper motions characterise of themselves the nature of their companionship. For either they keep on together or they show signs of incipient separation, slowly but surely marking the distinction between a lasting union and mere temporary contiguity. In the latter case the movement of one of the stars referred to the other necessarily proceeds along a straight line, so that rectilinear displacement is an infallible mark of an optical couple. One curiously close (Σ 1516) occurs in the constellation Draco. Two stars, of 7 and 7·5 magnitude, passed in 1856 so near to one another by the hazard of their paths nearly intersecting, as to present the effect of two points of light, one inch apart, at a furlong's distance from the eye. Their angular separation, then only 2″·6, is now 13″, and it will continue to grow indefinitely. Their absolute disconnection has been confirmed by direct measurements showing them to differ extremely in remoteness from the earth. The larger of the two, by one

[1] *Comptes Rendus*, t. lxxxvii. pp. 836, 872.
[2] Monck, *Knowledge*, vol. xii. p. 170.

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of those singularities which abound in the heavens, forms a genuine pair with a star very much fainter than its spurious companion.

From what has been said, it is clear that a good deal of patience is needed for the investigation of double stars. The facts about them must often be allowed to ripen for a long time before they can be turned to account. Sooner or later, however, their fruit cannot fail to appear. There is, perhaps, no other branch of science in which industry is so sure to be rewarded with definite results. The first step is to separate perspective from physical couples; this can only be done by the persistent repetition of exact measures. The next is to detect nascent circulatory movements in true binary pairs, or to keep watch on them as they progress. Their careful comparison with theory may at any time bring surprising novelties to light. For each stellar system is in effect a world by itself, original in its design, varied in its relationships, teeming with details of high significance. But at present only an imperfectly traced outline of the construction of some three-score among hundreds of them is before us; their multitude distracting attention. Yet it would be better to make intimate acquaintance with one than to know a score superficially. All the resources of modern inventiveness should be enlisted in these inquiries. Not only the revolutions, distances, and masses of double stars, their movements *across* and *in* the line of sight, should be determined with ever-increasing precision, but their colours and magnitudes, and above all, their separate spectra, both visual and photographic, should be recorded. By such means as these, real knowledge will be augmented far more than by the most brilliant success in the telescopic detection of new pairs. This has its own interest and value, but the recesses of sidereal structure must be otherwise explored.

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CHAPTER XII

STELLAR ORBITS

THE strong presumption that the law of gravitation would prove truly universal has been fully borne out by investigations of stellar orbits. Binary stars circulate, it can be unhesitatingly asserted, under the influence of the identical force by which the sun sways the movements of the planets, the earth the movements of the moon. This, it is true, does not admit of mathematical demonstration, but the overwhelming improbability of any other supposition enforces an almost equal degree of certitude.[1] The revolutions of the stars are hence calculable, because conducted on familiar principles; their velocities have the same relation to mass, their perturbations may lead to similar inferences as in the solar system.

Observations, however, must precede calculations; and they are rendered arduous in double stars by the extreme minuteness of the intervals to be measured. Many revolving pairs never separate to the apparent extent of a single second of arc; yet this fraction of a second may represent, in abridgment, a span of some thousands of millions of miles. Infinitesimal errors, magnified in this proportion, become of colossal importance, and often impenetrably disguise the real aspect of the facts.

For determining the relative situations of adjacent stars, two kinds of measurement are evidently needed. The first gives their distance apart, the second the direction of the line joining them as regards some fixed line of reference. That selected is the "hour-circle," or great circle passing through

[1] Tisserand, *Bulletin Astronomique*, t. iv. p. 18.

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the pole and the larger star, and the angle made with it by the line of junction of the pair is called their "position-angle." It is counted from 0° to 360°, in a direction opposite to that of the movement of watch-hands, and a star is hence said to be in direct revolution if its circuit is from north to south through east, but in retrograde revolution, if it is oppositely pursued.

Now the successive places, from year to year, of the moving star, obtained in this way with absolute accuracy, would fall into a perfect ellipse, the foreshortened delineation, as it were, of the real ellipse traversed in space. For the star's path is seen by us projected against the sky, or rather upon the plane touching the sphere at that point, while the actual orbit may lie in any one of an infinite number of planes. The two curves, nevertheless, have relations by which one can be deduced from the other with geometrical certainty. Both are ellipses, and in both the "radius vector," or line drawn from the satellite to the primary, describes equal areas in equal times. But the position of the chief star at the focus of the real ellipse is not maintained in its perspective representation, in which the "projected focus" is often quite unsymmetrically placed. Fig. 22 shows in juxtaposition the apparent and actual ellipses traversed by *a* Centauri, as delineated and computed by Dr. See. The distorting effects of perspective can be estimated by noticing that, while the true epoch of periastron was in 1875, the stars nevertheless continued to draw together optically until 1877. Once then the *seeming* orbit of a binary star is thoroughly ascertained, the problem of determining its *actual* orbit is as good as solved, the transition from one to the other being effected by a mathematical operation of no considerable difficulty. Even when the seeming orbit is a straight line the process remains feasible, and in fact one of the most reliable stellar theories relates to a couple, the movements of which are conducted in a plane passing, it may be said, accurately through the earth.[1] The stars of 42 Comæ Berenices appear simply to oscillate to and fro in a period of somewhat less than twenty-six years, never diverging to a greater extent than about half a second,

[1] O. Struve, *Monthly Notices*, vol. xxxv. p. 367; *Atti dell' Accad. Pont.* t. xix. p. 259.

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and closing up completely twice in the course of a revolution. Discovered by Struve in 1827, they have since then six times presented an aspect of indivisible singleness. Other couples

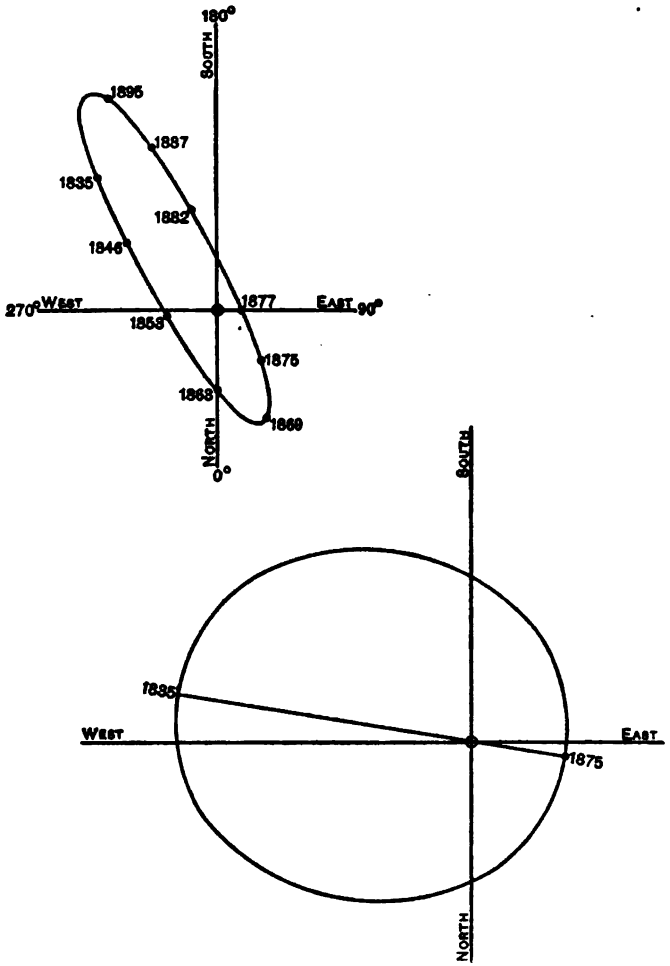

FIG. 22.—Apparent and real Orbits of Alpha Centauri. (The reduced diagram of the apparent ellipse in Newcomb's *Stars* has been availed of.)

travelling in paths seen nearly edgewise are γ Coronæ Borealis with a period of ninety-five, 44 Boötis with one of 261 years, and a binary in Ophiuchus (Σ 2173) revolving in forty-six years.

Nothing would at first sight seem easier than to lay down,

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from a sufficient store of data, the apparent track of a star. Yet the task is often a most embarrassing one. Owing to the excessive minuteness of the quantities concerned, the best observations can give only loose approximations to the real facts. The margin of uncertainty, always very wide, at times exceeds any reasonable limit, and computers are hence obliged, as a rule, to reject some part of the materials before them as misleading and incompatible with the rest. But the exercise of discretion leads to diversity of results, and totally different orbits can thus be derived from the same set of observations by varying their treatment so as to distribute differently their inherent errors. Where only a moderate arc of the orbit has been described, the problem of ideally completing it admits, from the indeterminateness of its conditions, of no rigid solution. One might, in Mr. Burnham's opinion, as well guess the period as go through the formality of calculating it.[1] When the companion of Sirius, for instance, had been eighteen years under scrutiny, it was still impossible to decide whether it would return to its starting-point within the half-century allotted to it while still an unseen agency of disturbance, or depart on a remote excursion from its primary, demanding some hundreds of years for its accomplishment.[2]

In no department of astronomy is the mischief of "personal equation" so sensible as in the measurement of double stars. Nearly all available data are prejudicially affected by it, and those emanating from different individual sources are thus often rendered exceedingly inharmonious. Much labour and ingenuity have been spent in determining its direction and amount for various observers, with a view to freeing their results from its effects; and after all, it remains a question whether the observations so elaborately corrected are not more misleading than in their "raw" state.

All these complications might be at once swept away if it were possible effectively to substitute the camera for the micrometer. The photographic method leaves no room for systematic, very little for accidental errors. G. P. Bond, of Cambridge (U.S.), showed in 1857, long before the introduction of the modern "dry plates," its wonderful capabilities

[1] *Popular Astronomy*, vol. i. p. 246.
[2] Plummer, *Monthly Notices*, vol. xlii. p. 63.

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for the accurate registration of the varying relative situations of double stars;[1] and those capabilities were more fully realised in 1886 by the skill of the MM. Henry. Some specimens of the Paris photographs of double stars may be inspected in Fig. 23. The repeated impressions shown of each pair were obtained by allowing free play to the diurnal motion during certain definite intervals between successive short exposures. The line of displacement of the stars traces out consequently part of a circle of declination, and their angles of position are directly measurable from plates embodying the data for their own orientation. The exactitude of determinations from them proved very remarkable; for ζ Ursæ Majoris the "mean error" of single measures of distance amounts to only $0''{\cdot}077$, of

FIG. 23.—Four Double Stars photographed at Paris. (Mouchez, "Photographie Astronomique.")

angle to $0{\cdot}^{\circ}55$.[2] And this is no illusory precision, but the statement of an unalterable fact. Unfortunately, however, the calculation of stellar orbits from photographic measures must long continue impracticable.

Their application is at present restricted to such pairs as are neither very unequal nor very close. The diffusive brightness of Sirius, for instance, leaves no possibility of getting a separate print of its companion, nor could even the much lesser disparity between the stars of δ Cygni be made compatible with the distinct self-portraiture of both. Again, the minimum interval at which even perfectly equal couples have hitherto been successfully photographed exceeds two seconds, closer objects running together on the plate. But the closer objects are just those most likely to be in rapid circulation; and measures of any others are only in a remote sense useful. In

[1] *Astr. Nach.* No. 1129.
[2] Mouchez, *La Photographie Astronomique*, p. 44.

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proportion, then, as star-couples lend themselves to photographic delineation, they are unprofitable to computers; while those that repay computational labour for the most part evade registration with the camera.[1] There are no doubt exceptions, such as Castor and α Centauri; and a yearly photographic record of each pair of the kind would eventually supply a stock of facts impaired in value by no perplexing inconsistencies. The apparent orbits of revolving stars will be virtually inscribed, one may hope, in future collections of negatives. The process of drawing a smooth curve will then no longer admit any wide latitude of discretion; and the representative ellipse, instead of threading its way amid a straggling crowd of outlying observations, will pass, not indeed actually *through* (which would imply the annihilation of error), but very close to all the given places.

Above eighty stellar orbits have so far been computed by Doberck, Gore, Glasenapp, Burnham, See, and others. But for the most part tentatively, nor always with success. Predictions are often at fault; orbits are assigned only to be discarded; the moving stars show themselves regardless of the trammels of theory. Thus, the persistent approach, since 1887, of the components of Castor makes it certain that the millennial cycle ascribed to them by Thiele is much too long, and suggests, even apart from calculation, that Sir William Herschel's estimated period of 342 years may be nearer the mark. The movements, on the other hand, of the fine southern pair, 6 Eridani, demand a continually lengthening time-allowance; and Mr. Burnham was inclined, in 1893, to regard them as rectilinear, that is, of a definitively separatist character.[2] The stars, none the less, seem at present to be conforming pretty closely to Mr. Gore's orbit, which should be completed in 302 years.[3]

Premature attempts to determine stellar revolutions are strongly deprecated by Mr. Burnham. Some computed orbits are so purely provisional that, as he points out, many others of a totally different form might be substituted for them without doing any violence to the observations. Among the

[1] W. J. Hussey, *Publ. Astr. Soc. Pacific*, No. 74, p. 102.
[2] *Astr. and Astrophysics*, vol. xii. p. 588.
[3] Innes, *Reference Cat.* p. 13 A.

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earliest of known couples is ζ Aquarii, divided by Father Christian Mayer in 1777 into equal components of the fourth magnitude. They are in slow circulation, having described in the course of a century and a quarter, an arc of less than 60°. From the scanty data thus supplied, Dr. Doberck has derived an orbit traversed in 1578 years, the longest period yet found for a binary system. But it is, or may be illusory. Mr. Burnham scarcely goes too far in saying that the measures of at least 500 years must be available before a satisfactory theory of this star's revolutions can be formulated.[1]

An opposite instance of uncertainty in calculation is afforded by δ Equulei, which now ranks as the quickest of visual binaries. Discovered by Otto Struve in 1852, it was watched through many complete circuits, each of which was, until 1900, held to occupy $11\frac{1}{2}$ years. In that year, however, Professor Hussey expressed a suspicion that the admitted period was just twice too long;[2] and it was amply justified by the star's subsequent behaviour.[3] Confirmatory spectroscopic observations have also been made;[4] and the pair promises to supply a most useful link between stars measurable with the micrometer and stars only resolvable on prismatic negatives. It was long ago perceived[5] that the combination of both methods, if rendered practicable, would lead to a far more complete acquaintance with the systemic conditions of stars than the employment of either of them separately. The capabilities of one, in fact, fill the lacunæ left by those of the other. Stellar orbits as computed from visual data are of undetermined size. Their distances from the earth have to be further ascertained before the scale of their construction becomes known. But it can also be derived, under favourable circumstances, from spectroscopic measurements of velocity in the line of sight. For these give, in miles per second, the rate of circulation of such star-pairs as prove amenable to them; and the rate of travel and the period virtually combine to state the dimensions of an orbit lying in a known plane. The mass

[1] *Pop. Astr.* vol. iv. p. 475. [2] *Publ. Astr. Soc. Pacific*, No. 76.

[3] *Publ. Lick Observatory*, vol. v. p. 205.

[4] *Lick Bulletin*, Nos. 4, 32.

[5] Fox Talbot, *Report Brit. Ass.* 1871, pt. ii. p. 34; Niven, *Monthly Notices*, vol. xxxiv. p. 339; Palisa, *Astr. Nach.* No. 2941; Rambaut, *Proc. R. Irish Acad.* vol. iv. ser. ii. p. 663; T. J. J. See, *Astr. Nach.* No. 3314.

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of the stars pursuing it and their parallax can thence easily be deduced. And Professor Hussey accordingly derived for δ Equulei a combined attractive power nearly twice that of the sun, and a parallax corresponding to a light-journey of 46 years. These results are the first of substantial value obtained by the application of the spectroscope to a telescopic double star.

The pair that comes next to δ Equulei in rapidity is κ Pegasi, divided by Mr. Burnham in 1880 into 4·3 and 5·0 magnitude components, not much above one-tenth of a second apart. They have since then performed more than two revolutions (period 11½ years) in an orbit viewed by us under an angle of only 9°, and consequently foreshortened into an exceedingly narrow oval, the oscillations of the stars in which can be followed only with the most perfect appliances.

A standard collection of forty stellar orbits, with new elements calculated by himself, was published by Dr. See in 1896.[1] Twenty-eight among them have periods falling short of 100, fourteen of 50 years; and these comprise some of the best-determined, though most recently discovered pairs — ζ Sagittarii, travelling in 18 years, 9 Argûs in 22, 85 Pegasi in 24, β Delphini in 27 years. The longest stellar period likely to be authenticated is that of 370 years, assigned by Dr. See to σ Coronæ Borealis, discerned by Herschel as double, August 7, 1780. Yet, thirty years ago, Doberck found it to need 846 years to finish a circuit; and he was an expert in researches of the kind. In general, as Mr. Burnham has insistently urged, revolutions require to be finished, or almost finished, before they can be said to be ascertained. Among the best stellar theories extant is that of ξ Ursæ Majoris, one of two fourth-magnitude stars marking the hindmost paw of the Great Bear. Divided by Herschel in 1780, this couple was made by Savary, in 1828,[2] the subject of the first experiment in the extension of Newtonian principles to the sidereal universe. It succeeded; for the stars were found to describe, as nearly as could be expected, the orbit calculated for them on the supposition that their mutual gravitation was the influence binding them together into a moving system. The

[1] *Evolution of the Stellar Systems*, p. 243.
[2] *Conn. des Temps*, 1830, pp. 56, 163.

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validity throughout the universe of Newton's law has never since been open to serious question.

The path of ξ Ursæ has of late been several times re-investigated, and with results so concordant as to give a strong assurance of their approximate accuracy. It is a considerably elongated ellipse, the eccentricity being expressed by the fraction $\frac{2}{3}$, which is just twice that of the orbit of Mercury, half that of the orbit of Encke's comet. The period of traversing it is 60 years; its semi-major axis would subtend, if seen without foreshortening, an angle of $2\frac{1}{2}''$, and it lies in a plane inclined 56° to the plane touching the sphere at that point.[1]

We are ignorant of the mass of this system because we are ignorant of its distance from the earth; but whatever its distance and whatever its mass, there seems no doubt that the stars conjoined in it are intensely luminous. If of the same mean density, they must be, square mile for square mile of surface, of about two and a half times the solar brightness.

Determinations of the distances of binary stars are of special interest from their leading to a knowledge of their masses. The connection is easily explained. Angular measurements, which are the only ones possible to be got of objects out of tangible reach, are convertible into definite linear values when the radius of the sphere they refer to becomes known—in other words, when the interval of space between the eye and the objects measured is ascertained. So that the dimensions, in seconds of arc, of the orbits of stars at determined distances give at once their dimensions in millions of miles, whence, with the help of their periods of revolution, their masses easily follow. For by the law of gravity the attractive power of any system is proportional to the cube of the mean distance of the bodies composing it, divided by the square of their period. Employing, then, as a unit of space in this little calculation the distance of the earth from the sun, and the year as our unit of time, we get the mass of each pair of revolving stars in terms of the sun's mass. It comes out, of course, larger in the ratio of the cube of the distance for the

[1] Data on these several heads, together with others defining the situation of periastron and of the line of intersection of the orbital and reference planes, constitute what are called the "elements" of a star's movements.

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same period, and smaller in the ratio of the square of the period for the same distance. Swiftly-moving and spacious systems contain accordingly great quantities of matter, sluggish ones comparatively little. Many radiant couples maintain, decade after decade, an all but absolute fixity. Alpha Crucis, 95 and α Herculis, γ Arietis are examples. The nascent displacements of ζ Ursæ Majoris suggest the possible accomplishment of a circuit in 10,000 years; those of γ Delphini might consist with a period of four millenniums. This strange inactivity intimates for the stars displaying it either an exceedingly small mass, or an inconceivable remoteness from the earth.

A list of binaries moving in known orbits for which parallaxes have been ascertained, will be found in Table IV. of our Appendix. It is unfortunately brief; yet it embodies some important information. One of these pairs, 85 Pegasi, was divided by Burnham in 1878, and completed in 1904 its first observed round. The components, although no brighter than sixth and eleventh magnitudes, exert a gravitating power (from Burnham's elements)[1] eleven times that of our sun. They wear the aspect, as Mr. Gore remarks, rather of a sun and planet than of two suns. The primary centuples the light emitted by its satellite, and there is just the disparity between them that would be presented by the sun and Jupiter if of the same intrinsic brilliancy. These would, on the condition supposed, and, at the distance (attributed to 85 Pegasi) of sixty light-years, show as a pair of $7\frac{1}{2}$ and $12\frac{1}{2}$ magnitude, never above $0''{\cdot}28$ asunder. The utmost powers of the great Lick refractor would scarcely be adequate for their separation; but the real stars being respectively four times brighter than the illustrative sun and planet, can be kept under watch and ward.

The masses of eight visual couples are fairly well known, and their total value is just that of thirty-one suns. On an average, then, any one of these systems contains nearly four times as much attractive energy as the solar system, each individual star being equal in this respect to a pair of suns like ours. Were the extension of this result legi-

[1] *General Catalogue*, p. 270; Comstock, *Astroph. Journ.* vol. xvii. p. 223. The parallax of 85 Pegasi is too small to be well-assured.

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timate, the distances of all stars revolving in ascertained orbits might be inferred from their assumed massiveness (since the relation between distance and mass is convertible), and upon this principle Mädler derived what he called the "hypothetical parallaxes" of binaries,[1] reckoning, however, the mass of each pair to be only that of a single sun. This estimate is now seen to be much too small, and the distances founded upon it to fall proportionately short of the truth.[2] But, indeed, no general conclusions of the kind are fit for application to individual cases. The range of variety is so great that only simulated knowledge can be obtained in this way. Yet collective inferences are not therefore worthless. Thus, from averaging the masses of only eight binaries, we have gathered plausible grounds for believing our sun to occupy a low rank as a centre of attraction. It may be, nevertheless, that the swifter binaries, which can at present alone figure on such a list, give too high an average mass.

Calculations based upon the orbital elements of revolving stars tell nothing of their *relative* masses. They apply only to the common stock of matter in each system, leaving its distribution to be otherwise tested. This cannot be done except through the due apportionment of movement between the members of the system—an arduous task, just begun to be grappled with.

There is no such thing in nature as a stationary body round which other bodies circulate. Answering motion there must always be, though on a scale reduced in the exact proportion that the mass is increased. The earth, for instance, describes, under the influence of the moon, an ellipse precisely similar to that described by the moon under the influence of the earth, but eighty-one times smaller. And the sun corresponds in the same way to the revolutions of every one of the planets, notwithstanding that the centre of his movement as regards each of them, with the single exception of Jupiter, lies far beneath his own surface. Binary stars, however, are

[1] *Der Fixsternhimmel*, p. 82.

[2] The masses of revolving stars vary, *cæteris paribus*, as the cubes of their distances from the earth. Of systems identical in period and apparent movement, one twice as remote as another would be eight times as massive, one three times as remote, twenty-seven times as massive, and so on.

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probably often almost equally massive, and therefore almost equally mobile bodies. The fixity of one member of each pair is purely conventional—an indispensable fiction without which measurements would be impracticable. Those actually made give the sum of the movements of both stars, and an orbit computed from them represents the sum of their distinct orbits. Identical in shape and position with the true ellipses, it differs from them only in size, its linear dimensions in any direction being equal to both theirs taken together.

The genuine centre of movement of two mutually circling stars is their common centre of gravity, which lies on a straight line drawn from one to the other, at a distance from each inversely proportional to its mass. The strictly similar orbits traversed by each are then spacious in the same inverted ratio. The larger star performs the smaller circuit, and *vice*

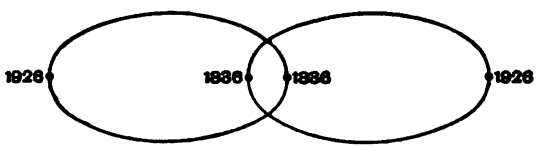

FIG. 24.—Orbits of the Component Stars of Gamma Virginis.

versâ. In the case of their equality, their orbits must intersect if elliptical, but coincide if circular, when the stars will pursue each other along the same track, while occupying in it, at each successive moment, diametrically opposite positions; nor could either, during an eternity of undisturbed revolution, gain a hair's breadth upon the other. But circular movement is not even approximated to by telescopic binaries, which usually follow highly eccentric paths.

We may take γ Virginis as an example of a pair moving in equal ellipses, the relations of which are shown in Fig. 24. They have, it will be seen, a common focus, the seat of the centre of gravity, from which the stars (being of equal mass) must always be equally distant. Neither can approach to or recede from this point of origin of the force acting upon them without the other simultaneously doing the same; the two must be in periastron and retire towards apastron together, losing and subsequently regaining velocity by the same grada-

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tions. The stars of α Centauri also travel in orbits sensibly equal, but much less elongated than those of γ Virginis (see Fig. 25).

The movements of unequal stars are similarly conducted. That is to say, the *proportion* of their respective distances from the common focus is invariable. They are accordingly always found in corresponding parts of their orbits, and at opposite ends of a right line passing through the focus. The manner of their revolutions can be realised by a glance at Fig. 26, representing the orbits of Sirius and its companion, the small ellipse belonging of course to the bright star.

Obviously, from what has been said, knowledge of the relative masses of binary stars would ensue upon knowledge of the relative dimensions of their separate orbits. This, indeed, is not within easy reach. Refined measurements, in a

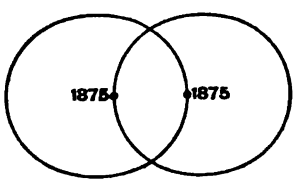

FIG. 25.—Orbits of the Component Stars of Alpha Centauri.

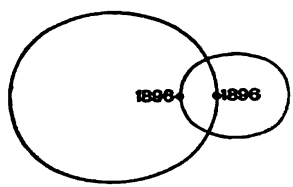

FIG. 26.—Orbits of Sirius and its companion.

prolonged series, of the individual components must first be secured, either with the transit-instrument or by micrometrical reference to some adjacent star.[1] From the proper motions of binary systems information of the desired kind may, in some cases, be elicited; for the track pursued by each star is necessarily, if their orbit be seen under a fairly wide angle, a sinuous one, like that of the moon round the sun, while the centre of gravity of the two advances uniformly in a straight line. Now this neutral point was, by Mr. Stone in 1876,[2] and again after twenty years by Mr. Roberts,[3] fixed about midway between the components of α Centauri. They are, accordingly, almost equally massive; yet the ratio of their luminosity is as four to one. Sirius, again, deviates from rectilinear motion to nearly half the extent that its companion does; it is, then, twice as massive, but 4300

[1] Pickering, *Proc. Amer. Acad.* vol. viii. p. 6 (1881).
[2] *Monthly Notices*, vol. xxxvi. p. 258. [3] *Astr. Nach.* No. 3360.

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times more luminous. And evidence of the same nature shows Procyon, while outshining its satellite 4700 times, to outweigh it no more than seven times. Analogous instances are gradually multiplying. Professor Comstock has ascertained that the faint companion of 85 Pegasi contains more matter, in the proportion of five to three, than its comparatively brilliant primary;[1] and similarly, a fourfold predominance in mass is assigned by M. Adalbert Prey to the six times less brilliant member of the interesting pair 70 Ophiuchi.[2] There remain six couples, the relative masses of which have been determined by Mr. Lewis from the Greenwich meridian observations. They are: γ Virginis, ζ Herculis, η Cassiopeiæ, o_2 Eridani, ξ Ursæ Majoris, and ξ Scorpii. Only for the first a normal result (if we may call it so) was obtained. The stars of γ Virginis seem perfectly matched in every respect—in average lustre, in spectrum, and in attractive power. In all the other pairs, varied degrees of disparity were met with, the component inferior as regards light being uniformly superior in the government of motion. In the system of ζ Herculis, which revolves in thirty-five years, the mass seems evenly divided, while no more than one-sixteenth of the total light is given by one of its members. Mr. Lewis has, moreover, detected anomalies in the movements of this pair suggesting the perturbative influence of an invisible body. The disproportion between mass and luminosity, which appears to be rather the rule than an exception among binary stars, has a most important bearing upon their physical history; but we shall not learn its full meaning until distinctions of spectrum are correlated with discrepancies in relative brightness.

Professor Pickering[3] and Mr. Monck[4] of Dublin separately perceived the existence of a relation between the movements and magnitudes of binaries, rendering it possible to determine their comparative luminous power proportionately to mass quite independently of their distances. It is necessary, however, to assume either that the components of each pair

[1] *Astroph. Journ.* vol. xvii. p. 223. [2] *Astr. Nach.* No. 3946.
[3] *Proc. Am. Acad.* vol. viii. p. 14 (1881).
[4] *Observatory*, vol. x. p. 96; *Knowledge*, vol. xii. p. 141; *Journ. Brit. Astr. Ass.* vol. viii. p. 179.

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are of similar quality in this respect, or else that one of them is of negligeable mass; nor does the formula distinguish between extent of surface and intensity of shining. The bodies considered may owe their differences in "mass-brightness" either to variety in mean density, consequently in the extent of shining surface, or to variety in actual brilliancy, area per area. The effects observed by us would be the same.

The results obtained confirm the prevalence of astonishing varieties in the emissive powers of stars. Taking ξ Ursæ as the standard pair, Mr. Gore calculated in 1891[1] the relative brightness of about sixty binaries moving in determined orbits. The tabulated figures are curious, even setting aside such objects as Castor and γ Leonis, which came out phenomenally brilliant because of the exaggerated length of the periods assigned to them by earlier computers. The duskiest stars in the list are those composing o_2 Eridani, which revolve in 180 years, and considerably exceed the sun in gravitating power, although claiming respectively only ninth and tenth magnitude rank. Admitting their density to be the same as that of ξ Ursæ, they seem to be intrinsically 660 times less luminous. On the other hand, λ Ophiuchi and γ Coronæ Borealis are, the first, twenty-nine, the second, twenty-one times more brilliant; ζ Herculis and γ Virginis, notwithstanding the difference of their spectral types, are about on a par in this respect, each couple shining with five times the standard lustre; while 70 Ophiuchi and η Cassiopeiæ maintain the similarity of their general character by their agreement in possessing a surface-brightness only one-third that of ξ Ursæ. The only rule governing these diversities is that, on the whole, Sirian stars are much more lustrous proportionately to their masses than solar. Corresponding data regarding stars with banded spectra would be especially valuable; but are unattainable, since objects of the kind are usually immobile, or inordinately slow in circulation.

The most striking general peculiarity of binary orbits is their high eccentricity. Nearly all of them are greatly more oval than the planetary paths round the sun, and a large proportion approach to cometary shape. In the "mean stellar ellipse," the focus of revolution is situated just half-

[1] *Proc. Roy. Irish Acad.* vol. i. No. 4, 3rd series.

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way between the centre and one of its extremities. The stars are, accordingly, separated at apastron by four times their periastron distance. "The average eccentricity among the double stars," Dr. See writes,[1] "is more than twelve times that found in the planetary system, and this extraordinary result is manifestly the expression of a fundamental law of nature." Indeed, an improved star-orbit is commonly more elongated than the one it replaces. Professor Hussey, for instance, in recalculating the elements of δ Equulei, found it necessary to triple the previously assigned eccentricity.

The circulation of binary stars is indifferently retrograde or direct. No tendency is perceptible towards concordance regarding the direction in which their tracks are pursued. Nor do they affect a common plane. They lie at all possible angles towards the Milky Way, and seem wholly exempt from its influence.[2] The existence of a fundamental plane of movement would be of high significance as regards the history and relations of the sidereal world; yet the whole drift of modern research suggests, rather than the close and rigid union between its parts which it would indicate, a loose connection destined to be extensively modified by time.

[1] *Evolution of the Stellar Systems*, p. 251.

[2] *Ibid.* p. 248. An analogous conclusion had been somewhat earlier reached by Miss Alice Everitt.

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CHAPTER XIII

VARIABLE DOUBLE STARS

THE light-changes of double stars are commonly of a fitful and indecisive kind. They may affect one or both members of stationary pairs; but visibly revolving stars, as a rule, conspire to vary, if they vary at all. The alternating fluctuations of γ Virginis, discoverable only by close attention to the swaying balance of lustre between the components, are in this respect typical. Each may be described as normally of the third magnitude, and each in turn declines by about half a magnitude and recovers within a few days, yet so that the general preponderance during a cycle of several years remains to the same star. The existence of this double periodicity was recognised in 1851 by M. Otto Struve, who, however, despaired of investigating it with success in a latitude where the stars subject to it never rise more than 30° above the horizon.[1] Nor has anything more definite been since learned on the subject. Instability still persists. It is made evident by frequent inversions of the position-angle, according as one or the other component, taken to be superior in brightness, is chosen as the origin of measurement;[2] but no trace of regularity is apparent in these inversions.

The pair circulates in the most eccentric of ascertained stellar orbits (see Fig. 24). The ellipse traversed by γ Virginis in 194 years is, in fact, proportionately somewhat narrower than the path round the sun of Encke's comet, so that the stars will in 1934 be separated by at least thirty times the sky-interval between them in 1836, when they merged into

[1] *Observations de Poulkowa*, t. ix. p. 122.
[2] Gore, *Knowledge*, vol. xxii. p. 201.

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a single telescopic object. A spectrum of late Sirian pattern is combined with a perceptible tinge of yellow in their light.

Relative variability is in 44 Boötis still more marked than in γ Virginis. But here a fundamental disparity between the components is seldom and temporarily abolished. Noted by Herschel as considerably unequal in 1781, they appeared to him perfectly matched in 1787. And it is worth noting that they had in the interim passed periastron. Struve observed, June 16, 1819, a difference between them of two magnitudes, which had sunk to half a magnitude in 1833. Argelander found them precisely equal June 6, 1830; Dawes perceived, April 27, 1841, a slight advantage on the side of the usually smaller star; while the superiority of its companion was recorded by M. Dunér at Lund as ranging, during the years 1869 to 1875, from 0·4 to 1·3 magnitudes.[1] Since their changes, often simultaneous, are not always in the same direction, their combined variability has never been conspicuous, the brightening of one tending, on the whole, to neutralise the fading of the other. The stars of 44 Boötis, according to Doberck's elements, traverse a highly eccentric orbit in a period of 261 years. Their tints, varying from yellow and sky-blue to white and dull grey, cannot be without influence upon their photographic magnitudes, determined at Paris in 1886 to be 5·3 and 6. Their joint light, though of the same spectroscopic quality, has then only one-twelfth the intensity of that of γ Virginis.

The component stars of ζ Boötis when photometrically measured at Harvard College in 1883 were of 4·4 and 4·8 magnitudes, but the order of their brightness has been at least three times reversed during a century of observation.[2] Their period of revolution must be of prodigious length. From 1796 to 1841 they appeared fixed; then a very slow wheeling movement became perceptible, accompanied by a diminution of distance, and it now taxes the powers of the best telescopes to divide them.[3] Their spectrum is of the Sirian type.

[1] *Lund Observations*, 1876, p. 74.

[2] *Harvard Annals*, vol. xiv. p. 458; *Observations de Poulkowa*, t. ix. p. 143; Dunér, *Mésures Micrométriques*, p. 68.

[3] Crossley, *Handbook of Double Stars*, p. 299; Tarrant, *Journ. Liverpool Astr. Society*, vol. v. p. 77.

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An analogous object is α Piscium, made up of a fourth and a fifth magnitude star at 3″ distance, and revolving in a period unlikely to be much less than two thousand years. The larger certainly varies in light, and perhaps also in colour, the smaller certainly in colour, and perhaps also in light.[1]

An observation made by Mr. Tebbutt in New South Wales, August 22, 1887, gave a unique proof of the relative variability of a close double star in Virgo (OΣ 256). At its occultation by the moon on that night, the chief part of the light went out with the disappearance of the reputed lesser star, the component which had of late passed for its primary remaining still for a few moments separately but dimly visible.[2] Similar but less marked reversals had already been noticed by O. Struve and Dembowski in this slowly circulating pair.[3]

Dr. Anderson has alleged convincing proofs that θ Eridani, now of the third magnitude, was assigned first rank by Ptolemy and Al Sûfi.[4] The star is a fine pair just perceptibly revolving;[5] but there is nothing to tell which component has suffered most from the ebb of light since the tenth century, or whether it has affected both equally. The kind of variability most distinctive of double stars might be described as a tilting of the luminous balance, now in one direction, now in the opposite, according to no settled law. It is exemplified, according to M. Flammarion in γ Arietis; it is, or has been, also present in θ Serpentis, 38 Geminorum, π Boötis, ϵ Arietis, and many other couples, most, if not all of which give spectra of the Sirian type. Their agreement in the possession of this particular quality of light is the more remarkable from its being the badge in solitary stars of exceptional stability. Every "white star," so far known to be variable, has proved also to be compound; and those of the Algol class are so far from making an exception to this rule, that they rank with the swiftest of possibly existing binaries.

Among the very few helium stars which have had periods of light-change assigned to them are δ Orionis and

[1] *Harvard Annals*, vols. xi. p. 112; xiv. p. 433; Flammarion, *Catalogue*, p. 12.

[2] *Observatory*, vol. x. p. 391.

[3] *Obs. de Poulkowa*, t. ix. p. 327.

[4] *Knowledge*, vol. xvi. p. 124.

[5] Innes, *Reference Cat.* p. 20 A.

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S Monocerotis; and in each case on dubious grounds. The first is widely double; the second is the leading member of a straggling cluster, and was thought by Winnecke in 1867 to change from 4·9 to 5·4 magnitude in $3^d\ 10^h\ 38^m$. It has two close attendants, both probably fixed. The system has no appreciable proper motion. Both δ Orionis and S Monocerotis are now known to be spectroscopic binaries. The first was detected as such by M. Deslandres, the second by Professors Frost and Adams.

Y Virginis combines the display of a first-type spectrum with liability to considerable, though intermittent, variations in light.[1] Struck by its peculiar brilliancy, June 6, 1866, Schmidt investigated its history from the tenth century downward, and concluded it to fluctuate irregularly from the fifth to the eighth magnitude. The anomaly of such changes in a Sirian star was brought more into harmony with other examples by Burnham's division of it at Chicago in 1879, into two nearly equal components less than half a second (0″·47) apart.[2] His subsequent observations have given no satisfactory evidence of alteration, either in brightness or position, during twenty years.[3] This singularly interesting system should not be neglected by the possessors of great telescopes.

The variations of U Puppis in fourteen days, from 6 to 6·8 magnitude, detected by Mr. Espin in 1883,[4] derive added interest from the strong probability that they integrate the changes of two close components. The star is the chief member of one of Struve's wide fixed couples (Σ 1097); after being "elongated" by Dembowski in 1865, it was fully resolved by Burnham in 1875 into an unequal pair at an interval of 0″·80. No symptoms of orbital movement have as yet been derived from it, and those of luminous instability seem suppressed. The case recalls the effaced periodicity of S Monocerotis, and is, in a measure, typical. The spectrum is of the solar type.

A corresponding long-period star is η Geminorum, per-

[1] *Astr. Nach.* No. 1597; *Harvard Annals*, vol. xiv. p. 456; Gore, *Knowledge*, vol. xiii. p. 204.

[2] *Observatory*, vol. iii. p. 192.

[3] *Gen. Cat.* p. 126.

[4] *Monthly Notices*, vol. xlvii. p. 432.

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ceived by Mr. Burnham during a visit to Mount Hamilton in 1881, to form "a splendid unequal pair, likely to prove an interesting system."[1] Its revolutions, shown by remeasurements in 1897 to be in slow progress,[2] will deserve the more attention that they are the first attributed to an Antarian star. As a variable, η Geminorum may be described as an abortive specimen of the Mira class. Its phases, run through in a period of 229 days, are always ill-marked, and at times almost wholly suspended. The share of the companion in bringing about these arrests of change has yet to be determined. Indeed, the more potent influence may belong to a second, closer attendant apparent only through motion-shifts in the spectrum of the variable, detected by Professor Campbell in 1902. Should it prove to revolve in 229 days, the fact will be of great importance to the theory of long-period variability.

The short-period variable, δ Cephei, governs a somewhat similarly constructed system; but its sea-blue satellite is remote, and appears stationary. The primary of the chromatic pair, β Cygni, too, is undeniably variable, though its variations are of an elusive kind. It shifts quite capriciously on the light-scale from 3·3 to 3·9 magnitude;[3] and recovers by the same imperceptible gradations that it lost brightness. The fluctuations long imputed to the companion of δ Cygni[4] are probably of atmospheric creation.[5] The object, at all times difficult and delicate, is readily obliterated by air-troubles; the more readily, perhaps, because of its variability in colour. Struve found it of an ashen shade from 1826 to 1833; in 1836 of a bright red.[6] It has since generally appeared blue; but Dunér saw it once olive, at other times red; and intervals of greyness are on record. No orbit yet computed for this pair inspires much confidence; Mr. Gore's, with a period of 377 years, is doubtless the best derivable from insufficient materials.

The presumption of sympathy in light-change between intimately united stars, although recommended by appearances,

[1] *Monthly Notices*, vol. xlvii. p. 204; *Astr. Nach.* No. 2930.
[2] *Gen. Cat.* p. 76.
[3] Klein, *Astr. Nach.* No. 1663.
[4] Herschel and South, *Phil. Trans.* vols. cxiv. p. 339; cxvi. p. 376.
[5] Dunér, *Mésures Micrométriques*, p. 118.
[6] "Color comitis egregius," *Mens. Microm.* p. 297.

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has not yet been strictly tested; but the converse proposition, that agreement in light-change implies physical connection, is of all but self-evident truth. Two variables in Cygnus,[1] for example, situated 24″ apart, may safely be assumed to constitute a system, their "ruddy and cœrulean" tints being a confirmatory circumstance. A still more striking combination is presented by U Cassiopeiæ and a blue companion at 59″, with which its strong red glow at times contrasts splendidly. The principal star fluctuates irregularly from the sixth to below the ninth magnitude; the attendant from the eighth to the tenth. The probability of their being united by a special tie is overwhelming. Accordant variability of a conspicuous kind is an argument for its existence to the full as convincing as the possession of a common proper motion.

The crimson tint of U Cygni, discovered by Mr. Knott in 1871 to vary from above the eighth to below the eleventh magnitude in a period of 466 days, was described by Webb as "one of the loveliest in the sky." It is set off by the blue rays of a companion at 6″, which seems to fluctuate in colour, but little, if at all, in light. Their azure is, however, no mere optical effect of contrast, since (though capable of fading independently)[2] it survives without alteration the telescopic extinction of the adjacent red luminary. U Cygni is the only star belonging to the fourth spectral order open to a suspicion of being in systemic connection with a neighbour.

A good many variables have satellites as to which no such suspicion arises. Thus, the ninth-magnitude star within 46″ of the beautiful "carmine" tinted object S Orionis is undistinguished either by colour or change, and they hence very likely form only a perspective couple. The same inference applies to three small stars contiguous respectively to R Cassiopeiæ, R Crateris, and Mira Ceti, detachment through the proper motion of the variable being, in the last case, visibly in progress.

The light-changes of connected stars indicate duplicity as one of the causes tending to produce fluctuations of a certain ill-pronounced type. For we can safely assert, from the

[1] *h* 1470 = Lalande 38428.

[2] Birmingham, *Trans. R. Irish Acad.* vol. xxvi. p. 300; Gemmill, *English Mechanic*, vol. xlvi. p. 340.

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character of their spectra, that most of the objects exhibiting them would shine steadily if single. This relation is rendered the more significant through the possibility first obscurely brought into view by Sir Norman Lockyer's meteoritic theory, that variability of every kind depends for its production upon external action by closely circulating and to us invisible bodies. A test too may be furnished by fluctuating couples to the opinion that luminous instability belongs to a late stage of stellar existence. The contemporaneous origin and similar constitution of members of binary systems are indicated to our minds as highly probable. If this be so, development should, according to the received opinion, proceed, other things being equal, quickest in the smallest masses, more slowly in the larger.[1] Hence, if it were true that variability accompanied decline, companion-stars should, one might suppose, be far more unstable in light than their primaries. But this anticipation is far from being realised. Variable primaries are more frequently met with than variable satellites. It is scarcely, indeed, too much to say that in every undoubted case of variability in one member only of a pair, the member it distinguishes is the principal star. Nor, even if we were sure that the pace of evolution in star-systems is prescribed by mass, would it be safe to conclude anything as to its distribution from observed differences of brilliancy. Mass and luminosity are not comparable. Predominance in light, as we have learned from repeated experience, is no valid argument for predominance in quantity of matter. This circumstance adds both difficulty and interest to the far-reaching question of the origin, history, and mutual relations of conjoined stars.

[1] Lockyer, *Proc. R. Society*, vol. xliv. p. 90.

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CHAPTER XIV

SPECTROSCOPIC BINARIES

THE spectroscopic method of determining velocity has already been frequently referred to in these pages. We may now briefly explain the principle upon which it rests. This is easy to apprehend, but extremely difficult to apply. Christian Doppler of Prague pointed out in 1842 that the motion of a luminous source towards or from the eye, or of the eye towards or from a luminous source, must alter the refrangibility of the incident light. It must diminish it if the relative movement be of withdrawal; it must augment it if it be of advance. For refrangibility depends upon wave-length, and wave-length is the reciprocal of wave-frequency. In other words, the more vibrations are pressed into a given space, the shorter they necessarily are, and the more refrangible the ray they conspire to form. But clearly, the light-waves emitted by a body travelling towards us arrive in quicker succession than if it were at rest; they are shortened in the proportion of the rate of travel of the luminous object to the velocity of the propagation of light; and being shortened, they are rendered, *ipso facto*, more refrangible. An opposite effect is produced by receding movement. The light-waves from a retreating body are lengthened; there are fewer of them in an inch or a mile; and they are accordingly rendered less refrangible.

All this was fairly obvious; but it seemed questionable whether any practical outcome could be derived from the recognition of its abstract truth. The doubt was removed when Hippolyte Fizeau showed, in 1848, the feasibility of using spectral lines as standards of reference for measuring

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the changes of refrangibility due to end-on motion. The rays, bright or dark, included in the spectrum of the travelling object naturally shift with the whole of its light-gamut. By juxtaposition, accordingly, with corresponding rays otherwise derived, and, of course, in their normal places, the amount of their shiftings becomes known, and hence the direction and rate of the movement producing them. Even then, twenty years had to elapse before Sir William Huggins made his pioneering experiments on the radial velocities of the stars; and twenty years further before the method was perfected by the adaptation to it, through Dr. Vogel's initiative, of the camera.

The effects of motion on stellar spectra are illustrated in Plate X., which reproduces, by Sir David Gill's kind permission, one of the admirable spectrograms taken with the McClean telescope by his assistant, Mr. Lunt. The rays analysed were those of α Phœnicis, a star of solar type, which retreats from the sun at the rate of 82 kilometres per second, or nearly thrice as fast as the earth circulates in its orbit. Let us consider how this is learned from the photograph. Five strips of dispersed blue light are included in it. A section of the solar spectrum is shown in two of them; the same part of the spectrum of the star adjusted to precise correspondence with the solar prototype, appears in the fourth strip from the top. The dark lines are in both almost identical; and that many of them claim an origin from iron-vapour, can be seen by a glance at the iron-spark comparison-spectrum, in which the rays, obscure in the sun and star, shine by direct emission. Now the iron-spectrum is given twice: in the second, and in the fifth, or lowest strips; and there is a conspicuous difference between the presentments of it. One is strongly displaced relatively to the other. This displacement measures the motion-shift in the spectrum of the star. The iron-lines below are fiducial; they were photographed with the star, and served to determine its receding speed. The lines above were photographed with the sun, and being designed purely for purposes of identification, are arranged to coincidence with the star-lines. The glaring nature of the discrepancy between the adjusted and the non-adjusted iron-spectrum enables us to realise the possi-

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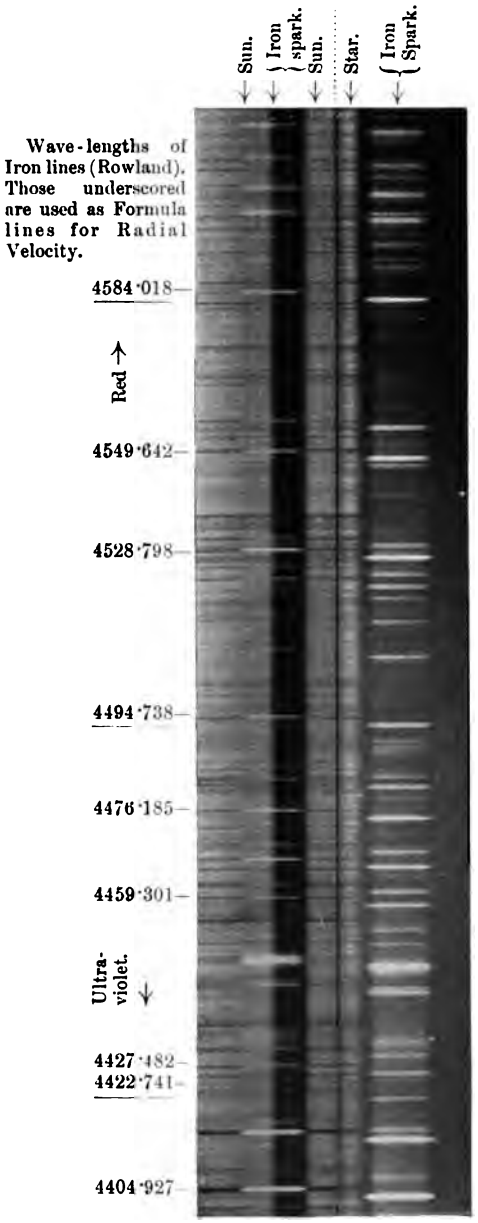

Original Negatives enlarged Seven Diameters.

Spectrum of *α Phœnicis* taken with the McClean spectrograph at the Cape Observatory on November 27, 1903, by J. Lunt; exposure three hours. Iron Comparison Spectrum. The Solar Spectrum is placed above the Star Spectrum. The Iron lines photographed with the Solar Spectrum enable the corresponding star lines to be identified. The star lines have a very large "shift" to the red, which corresponds to a velocity of 105 kilometres per second away from the earth, and 82 kilometres from ⊙.

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bility of appreciating, by similar means, alterations of wave-length due to velocities of no more than one or two kilometres a second.

Solitary stars, like our own, travel uniformly. Their rate of transport does not vary sensibly from month to month, from year to year, perhaps from century to century. But with binary stars the case is different. Besides the constant velocity belonging to the system as a whole, they circulate round their common centre of gravity; and the direction of their orbital movement as regards the earth is continually changing. Take, for instance, a pair revolving in the visual plane. At some given moment their total speed of revolution will lie across the line of sight. It will then be spectroscopically ineffective; the rays characteristic of its light will be in their standard places; no shifts will be perceptible. But when a quarter of a circuit from the points of conjunction has been described, and the stars are at the opposite nodes of their orbit, the direction of movement, having turned through a right angle, will be straight end-on. Hence the spectral lines of the components will show contrary displacements corresponding to the entire velocity of their mutual circling. Two good spectrograms, accordingly, taken at the critical instants of conjunction and elongation, suffice, at least theoretically, both for the elimination of translatory speed, and for the determination of the actual rate of revolution; and this, when the period is known, gives the size of the orbit in miles or kilometres. Evidently, spectroscopic measures at such times of visual pairs with securely computed elements would make us acquainted with their distance from the earth and joint gravitating power—even if their paths were inclined, at a considerable, though a known angle. The success of such investigations, it is true, long seemed remote; but it has now been achieved. Professor Hussey, in 1903, determined for δ Equulei a "spectroscopic parallax" which inspires no small confidence.[1] And still more recently, Dr. Palmer of the Lick Observatory has computed, from the radial velocities of α Centauri, a value for its parallax in all but exact agreement with that derived from the most skilful heliometric observations.[2] Few

[1] *Lick Bulletin*, No. 32, see *ante*, p. 168. [2] *Ibid.* No. 60.

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telescopic binaries, however, are circumstanced favourably enough to invite the application of the method. The conditions propitious to it are rapid motion in a plane not much inclined to the sight-line, and considerable brilliancy in both the moving objects. Pairs that are easily divided rarely circulate quickly enough for the discrimination of differences in their radial velocities; and the most rapidly circulating pairs are those most apt to defy visual separation. The spectroscope, in fact, finds its opportunities just where the telescope encounters baffling difficulties; and this reciprocal relation, while it has helped to give almost indefinite extension to our acquaintance with stellar systems, restricts opportunities for combining the methods, so as to connect the angular measures furnished by one with the linear orbital dimensions obtained by the use of the other.

Stars revolving in or very near the visual plane must undergo, at any rate, partial eclipses. They are comparatively few; the great majority move in paths sensibly, though variously inclined to it. But as the tilt increases, the proportion of the velocity available for spectroscopic measurement, because directed radially, obviously diminishes. Wholly inaccessible to it, in fact, are such couples—and they may be very numerous—as circulate approximately at right angles to the line of sight. For those with orbits intermediately situated, the apparent or measured radial velocity divided by the cosine of the angle of deviation from horizontality gives the actual radial velocity. If, for instance, the inclination amounted to 60°, only half the speed of revolution would tell in line-displacements. An average value for it of about 30° is regarded as probable;[1] and this would give 100 to 115 as the proportion of the observed to the true rates of circulatory motion. But estimates of the kind serve only to mislead if applied to individual systems. The safer course is to admit that, in the absence of occultation-phases, we can secure only minimum values for the velocities, distances apart, and masses of binaries spectroscopically detected and observed.

They are extraordinarily numerous. Professor Campbell showed, in 1902,[2] the probability that, among the entire

[1] Barr, *Astroph. Journ.* vol. xi. p. 248. [2] *Lick Bulletin*, No. 20.

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multitude of stars, one in six or seven is so constituted; and Professor Frost added wonder to wonder by the statement that helium-stars in particular yield so large a harvest of binaries that the chances are nearly even whether a given object of the kind will resist or surrender to the resolving powers of the spectroscope.[1] One of the most curious facts about close star-pairs is the prevalence of extreme inequalities of lustre between their components. In very many, one is brilliantly luminous, the other so far obscure that no spectrographic impression can be derived from it. Some satellites, again, shine dimly; traces more or less pronounced of their action on the sensitive plate are perceptible; while finally, twin-stars are occasionally met with scarcely distinguishable by quantity or quality of light. To this category belong ζ Ursæ Majoris and β Aurigæ, the former detected by Professor Pickering in 1889, the latter shortly afterwards by Miss Maury. In both, the spectral lines are periodically photographed as doublets, when the components of each pair, at their "elongations," are travelling full speed ahead and aback respectively, towards and away from the earth. The separation of the lines thus corresponds (allowance having been made for the constant velocity of the system as a whole) to twice the rate of circulation, diminished, as we have explained, in proportion to the inclination of the path traversed. Twice in the course of each revolution, stars of the kind we are now considering exhibit the phenomenon of doubled lines; at the intermediate epochs of conjunction, they give a single spectrum. By timing these alternations, a period of twenty days has been deduced for ζ Ursæ, one of four days for β Aurigæ. Miss Maury's binary, accordingly, changes its spectral aspect from day to day; and the indicated relative velocity of 150 miles a second shows it to possess at least five times the massiveness of our sun.[2]

A magnificent system of this type, but in comparatively slow circulation, is formed by Capella.[3] The light of a purely solar star, and of a companion somewhat less bright and some-

[1] Frost and Adams, *Astroph. Journ.* vol. xviii. p. 383.

[2] Vogel, *Sitzungsberichte*, Berlin, March 10, 1904.

[3] Campbell, *Lick Bulletin*, No. 6; *Astroph. Journ.* vol. x. p. 177; Newall, *Monthly Notices*, vol. lx. p. 418.

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what less massive, of the Procyon variety, are combined in this object; and they mutually revolve in 104 days at the apparent or minimum rate of about seventy miles a second. The parallax of Capella, though small, is assured; it gives a distance of forty light-years, whence we can infer that the joint lustre of the components exceeds more than a hundredfold the splendour of the sun.

Couples consisting of two bright members are much easier of detection than those of which one is obscure. Duplicated rays in a stellar spectrum attract attention even on a crowded plate exposed with an objective prism, in a manner to secure wholesale records; but the oscillations of single lines require the aid of a slit and a comparison-spectrum to make them evident. They evade notice unless the stars are separately studied. Yet, despite observational difficulties, about 75 per cent of the spectroscopic binaries (to the number of nearly 130) known at the end of 1904 have sensibly obscure companions. The first non-eclipsing star recognised as double by the mere swinging to and fro of solitary lines was Spica (*α* Virginis). Dr. Vogel thus determined in 1890 its revolution in four days round an attendant later shown to be very feebly luminous. Both members of the stately visual pair, Castor, on the other hand, circulate swiftly round bodies giving no sensible light. The quaternary system thus formed is of unique interest. Dr. Curtis,[1] the discoverer of one of the dark attendant stars (the other was found by Bélopolsky in 1896), has determined for it—provisionally assuming the correctness of Doberck's elements—a spectroscopic parallax of 0″·05, corresponding to a light-journey of 65 years, and implying a total mass for the four constituent globes nearly thirteen times that of the sun. But it seems to be very unequally apportioned. One of the revolving pairs exerts thrice the attractive power of its companion, while emitting only half as much light. The gravitational primary is the visual satellite, and *vice versâ*. Only through the association of telescopic with spectroscopic measures, practicable by a rare exception for Castor, can inferences regarding the mass of bright and dark pairs become legitimate. Nothing definite can, under ordinary circumstances, be affirmed on the subject. For one com-

[1] *Lick Bulletin*, No. 70.

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ponent being invisible, the size of their relative orbit remains absolutely undetermined; and the size of the relative orbit is a datum essential for computing the mass of the system, or even a minimum value for the mass, which, in our ignorance as to the lie of the orbit, is the utmost we could hope to arrive at. The relative orbit, as already explained, is the sum of the separate orbits; or, putting it otherwise, the path described by one star round a companion taken to be at rest. From its span, in conjunction with the period, the mass of the pair is deducible. There is no means of learning it without knowledge of these two elements. The masses of bright and dark pairs can then, as a rule, only be guessed at with the unwarranted help of arbitrary hypotheses. That of Spica, for instance, has been estimated at 2·6 times the solar mass; but the value has only the authority of a plausible conjecture.

From the measured movements of stars with shining companions, as already explained, the least possible amount of matter present in each system may be learned. The orbit spectroscopically determined being the foreshortened representation of the orbit actually traversed, is smaller in an unknown degree; and the mass of the moving bodies varies as the cube of the orbital radius. The error of mass-determinations hence grows in a triplicate ratio to the error of the linear dimensions directly obtainable. Minimum values, nevertheless, are better than none at all; they fix a limit of great importance; and for one species of crypto-double stars they may almost count as absolute values. These are eclipsing pairs in which both components are bright. Y Cygni is a favourable example. The opposite movements in its system may be spectroscopically elicited; the size of the relative orbit will thereby be given; and since its plane is fixed by the occurrence of a twofold eclipse, the joint mass of the components can be ascertained without dubious assumptions. Several Algol-variables appear to be similarly constituted; but their investigation awaits the leisure of overtasked spectrographers.

Few compound objects are more inviting to research than stars variable in short periods, though not through eclipses. Six have already been detected as spectroscopic binaries; and the resolution of all may be regarded as depending merely

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upon time and facility. The extreme interest of the questions connected with them is exemplified in ζ Geminorum, the radial velocity of which was found by Professor Campbell to be subject to a double periodicity, due, he surmised, to the influence of a second dark satellite;[1] yet the stable construction of a triple system on the indicated conditions seems a hopeless task. Again, κ Pavonis varies from 3·8 to 5·2 magnitude in a mean period of nine days, affected, according to Mr. Roberts's observations,[2] by an inequality amounting to ten hours, comprised in a cycle of eight years. The duplicity of the star was ascertained by Dr. Palmer in 1904;[3] and before long an answer may be furnished to the critical inquiry whether the disturbance of the light-period is reflected, or perhaps originated, by a disturbance of the gravitational period.

Nor is it short-period variables alone which yield to the motion-test. The division of stars that fluctuate irregularly, or in long periods, is of not infrequent occurrence. Such is η Geminorum, one of Burnham's unequal pairs, raised to a higher plane of complexity by the addition of Campbell's spectroscopic attendant.[4]

A period of about forty days is partially conformed to by the ebb and flow of luminosity in u Herculis, a helium-star visible, even at its dimmest stages, to the naked eye. Detected as binary by Mr. Adams[5] at the Yerkes Observatory, it revolves round a seemingly dark companion at a high speed, but in a period which has still to be ascertained. The investigation of the system constituted by ϵ Aurigæ is also incipient. Dr. Vogel's resolution of this object in 1902 into a bright unequal pair, with a relative velocity in the line of sight of nearly twenty-five miles a second, will be in the minds of our readers.[6] Now ϵ Aurigæ has, during the greater part of a century, been remarked for slight phases of light-change held to be quite capricious in their occurrence. Should Dr. Ludendorff's regularisation of them be verified by future observations, their twenty-seven year period will rank as by

[1] *Astroph. Journ.* vol. xiii. p. 90.
[2] He does not place implicit confidence in them, *Astr. Journ.* No. 563.
[3] *Lick Bulletin*, No. 60.
[4] *Ibid.* No. 20.
[5] *Astroph. Journ.* vol. xvii. p. 281.
[6] See *ante*, p. 105.

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far the longest that can be ascribed to any form of stellar light-change. And it will be of great importance to correlate with it, if possible, the star's period of orbital revolution. There is, perhaps, no object in the heavens of more pregnant interest than this variable spectroscopic binary.

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CHAPTER XV

MULTIPLE STARS

THE further resolvability of a great many double stars is one of the most curious results of modern improvements in the optical means of observing them. With every addition to the defining power of telescopes, the visible complexity of stellar systems has increased so rapidly as to inspire a suspicion that simple binary combinations may be an exception rather than the rule. The frequency with which those taken to be such have yielded to disintegrating scrutiny suggests at any rate some innate tendency, indicating that the duplicity of stars is no accident of nebular condensation, but belongs essentially to the primitive design of their organisation. Although we can never become fully acquainted with all the detailed arrangements of stellar systems, we are then led to suppose them far more elaborate and varied than appears at first sight. Each, we cannot doubt, is adapted by exquisite contrivances to its special end, reflecting, in its untold harmonies of adjustment, the Supreme Wisdom from which they emanate.

The continuance of the process of optical dissociation, begun by the splitting up of an apparently simple star, sometimes shows the primary, sometimes the satellite, not unfrequently both primary and satellite, to be very closely double. Ternary systems are accordingly of two kinds. In one, the smaller star consists of two in mutual circulation and concurrent revolution round a single governing body; in the other, an intimately conjoined pair guides the movements of an unattended attendant. The planetary type of construction is uncommon or unknown. No star has been *ascertained* to

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possess two or more companions circulating co-ordinately. Groups possibly indicating such a disposition of parts exist, but perspective may have a share in producing them. The variable S Monocerotis, with its two client-stars, is an example. Another is mentioned by Dr. See. Four extremely faint companions, at distances between 7″ and 39″ from a sixth-magnitude star in the Poop of Argo (Cord. G. C. 10534), have been detected by him and his predecessors. The group is thus commented on by him:—"Quintuple! Probably a complicated physical system; the only stellar system I know of constructed on a plan in any way analogous to that of the planets."[1] There is, however, at present no proof that the arrangement may not result, at least in part, from the chances of perspective juxtaposition.

Among the most interesting triple stars of the double-satellite description is the brilliantly coloured γ Andromedæ. The original components, of third and fifth magnitudes 10″ apart, remain *in statu quo* since they were seen by Father Mayer in 1777, but their secular journey together over an arc of 10″ establishes the genuineness of their relationship. In 1842 the sea-green companion was found to be itself double. With the 15-inch Pulkowa refractor, Otto Struve caught sight of a thin black line (representing probably a gap of some thousands of millions of miles), dividing it into two stars, the fainter of about sixth magnitude, which within fifty-five years completed a revolution in an orbit not much less eccentric than that of γ Virginis.[2]

A pair in some respects similar, but much fainter, is attached at about the same apparent interval to the lustrous white star Rigel. An excessively difficult object at the time of its detection, it later became impossible. Its elongation, suspected both by Burnham and Herbert Sadler in 1871,[3] was verified at Chicago and Mount Hamilton in 1878-79. Then, for nearly twenty years, no sign of duplicity could be elicited from it.[4] Change, under the circumstances, seemed much more probable than error; and its rapid progress was indicated by Professor Aitken's reobservation of the sapphire attendant

[1] *Astr. Journ.* No. 431.
[2] W. J. Hussey, *Publ. Lick Observatory*, vol. v. p. 45.
[3] *Astr. Register*, vol. xviii. p. 15. [4] Burnham, *Gen. Cat.* p. 59.

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upon Rigel,[1] as palpably double in 1898. Nevertheless, after two years, the evasive satellite was again undiscernible.[2] The riddle of its existence may be finally solved by the aid of a spectrographic apparatus of great light-collecting power.

A ternary group, corresponding to these two in plan but greatly enlarged in angular scale, consists of a 4·5 magnitude star, designated by Flamsteed 40, by Bayer o^2 Eridani, with a faint and far-away double satellite already referred to,[3] all three discovered by Herschel in 1783. The association of the pair with the large star at so great an interval as 82″ would be improbable, were it not certified by their possession in common of an exceptionally swift proper motion. An advance during the last century over a space nearly equal to a quarter of the moon's diameter has modified their relations only by a trifling approach to their primary of the dependent stars, due perhaps to slow circulation round it in an orbit presented edgewise to our sight.

They have, in the meantime, almost finished a circuit of one another, and will have completely finished it within about 180 years from the date of their detection.[4] And since their distance from the earth has been measured, the real size of their orbit and their joint mass are also known. We find then that the average interval between them is thirty-eight times that separating the earth from the sun, so that (their path being only moderately eccentric) they never approach as near to each other as Neptune does to our central orb, which they together surpass 1·6 times in gravitative power. But in their place, from which light reaches us in twenty years, the sun would shine as a fourth-magnitude star, while they combine into one of only ninth magnitude. Their feeble luminosity thus once more forces itself upon our attention, and compels us to reflect upon the possibility of whole systems existing in unimpaired mechanical perfection, but wrapped in perennial darkness. For what purpose existing, who can tell? The flight of our thoughts is short and the ultimate aims of the Maker are remote. Attempts to compass them are foredoomed to failure.

[1] *Pop. Astr.* December 1898, p. 585.
[2] *Lick Bulletin*, No. 11.
[3] See *ante*, p. 84.
[4] Burnham, *Monthly Notices*, vol. liii. p. 478.

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Double primaries occur as freely as double satellites; and their common centre of gravity presumably constitutes the focus of attraction for their remote attendants. Castor splendidly illustrates this plan of construction, carried out on a vast scale in its system, which includes five members; the lucid components, a far-off captive star borne in their train, and the obscure adjacent masses disclosed only by their spectroscopic effects. Another specimen is ϵ Equulei, one of Herschel's pairs, the larger member of which was again divided by Struve in 1835. The feat had become possible through the progress of orbital motion, the continuance of which has since rendered it easy. Signs of circulation in the 7·5 magnitude star at $11''$[1] are scarcely, if at all, perceptible. Yet it is an undoubted satellite of the close couple.

The movements of the third star (of 7·1 magnitude) in the ternary combination ξ Scorpii, *seem* to progress in an opposite direction from that of the close double star which controls them at an apparent distance of $7''$; but their nature and method are still imperfectly developed. The primary in this system consists of two fifth-magnitude stars, formerly just separable with a good 4-inch telescope, but now only $0''·7$ apart. The orbit assigned to them by Dr. See[2] approximates, in an unusual degree, to a circle, and is traversed in 104 years. Their spectrum is of the Sirian type. The eighth-magnitude companion of ϵ Hydræ has described, since its discovery by Struve in 1825, an arc of over 40°, at a distance of $3''$. Its blue tint is charmingly set off by the warm yellow of the chief star, divided by Schiaparelli in 1888 into a difficult pair revolving (by Professor Aitken's elements) in less than sixteen years. Possibly, the process of resolution has not reached its term; for Dr. Curtis measured, in 1900, fluctuations in the radial velocity of the leading component. They more probably, however, depend upon its revolution in the visual orbit.[3] Undoubted spectroscopic binaries nevertheless frequently occupy analogous positions. Besides the systems of ζ Ursæ Majoris, and η Geminorum, those of ξ Ursæ, β Scorpii, and κ Pegasi are thus composed. As a wide pair, κ Pegasi was noted by

[1] Flammarion, *Catalogue*, p. 139. [2] *Stellar Systems*, p. 178.
[3] *Lick Bulletin*, Nos. 4, 36.

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Herschel in 1786. The question is still open whether his eleventh-magnitude companion has any physical connection with the nuclear group. This consists of a fairly equal pair, recognised by Burnham in 1880,[1] and found to revolve in 11·4 years; together with an unseen companion to one of them, detected by Campbell in 1900, and completing its circuits in about six days.[2]

The relations of the stars compounded in β Scorpii are no less remarkable. Two, of respectively third and sixth magnitudes, were first observed by Herschel in 1779; the third, discovered by Burnham a century later, makes with the primary an extraordinarily difficult, unequal pair at $0''{\cdot}96$.[3] A fourth has been spectrographically measured by Mr. Adams.[4] It is a lustrous object with a helium spectrum, and revolves at high speed in a period estimated at $6^d\ 21^h$.[5] No visible *relative* movements have yet been perceived in the system of β Scorpii, which nevertheless asserts its organic unity by the harmony of its advance through space.

One of the most curiously interesting of all the stellar systems known to us is ternary from an optical, quaternary from a physical point of view. It is composed of one obscure and three bright members, all in comparatively rapid mutual circulation. The division of ζ Cancri, by Tobias Mayer in 1756, into a fifth and a sixth magnitude star about $5\frac{1}{2}''$ asunder was the preliminary to Herschel's further analysis. "If I do not see extremely ill this morning," he wrote on November 21, 1781, "the large star consists of two."[6] This was the earliest example of the decomposition of a double into a triple star. The next distinct view of these close objects (called for convenience A and B, the remoter star C) was obtained by Sir James South at Passy in 1825, but Struve's 9-inch Fraunhofer showed them easily, and they have never since been lost sight of. Reobservation at once rendered patent their swift movement of revolution. Before the close of 1840 they had, by resuming the positions in which they were originally

[1] *General Catalogue*, p. 234.
[2] *Astroph. Journ.* vol. xii. p. 257.
[3] *Monthly Notices*, vol. xl. p. 100; *General Catalogue*, p. 146.
[4] *Astroph. Journ.* vol. xviii. p. 69.
[5] *Lowell Observatory Bulletin*, No. 1.
[6] Crossley, *Handbook*, p. 247.

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observed, authoritatively declared their period to be not far from sixty years. And their orbit lies in a plane so nearly square to the line of sight, that foreshortening takes little effect upon it, and occultations are hence impossible. Although the maximum interval between the stars scarcely exceeds one second, and the minimum interval is no more than $0''{\cdot}2$, they never close up beyond the dividing powers of first-class instruments.

But the orbital movements of the couple A B make only part of a complex scheme of displacements. "This star," Sir John Herschel remarked in 1826, "presents the hitherto unique combination of three individuals, forming, if not a system connected by the agency of attractive forces, at least one in which all the parts are in a state of relative motion."[1] He added that, if really ternary, its perturbations must present "one of the most intricate problems in physical astronomy"; and Professor Newcomb holds it probable that the laws of motion in such combinations must, in general, be "too complicated to admit of profitable mathematical investigation."[2]

The star C apparently retrogrades round A B at an average rate of half a degree a year, indicating (if maintained with approximate uniformity) revolution in a period of 600 or 700 years. But this average rate is subject to very remarkable irregularities. The path traced out in the sky, far from being a smooth curve, is looped into a series of epicycles, in traversing which the star alternately quickens and slackens, or even altogether desists from its advance, while increasing or diminishing, by proportionate amounts, its distance from the centre of motion. This anomalous behaviour, detected by M. Flammarion in 1873,[3] was both detected and interpreted by Otto Struve in 1874.[4] The vagaries of the third component of ζ Cancri proved, from his investigation, to be very far from unmethodical. The accelerations which they included were shown to be perfectly compensated by retardations, and to be accompanied unfailingly by expansions outward of the parts of the track where they

[1] *Phil. Trans.* vol. cxvi. p. 326.
[2] *The Stars*, p. 164.
[3] *Catalogue*, p. 49.
[4] *Comptes Rendus*, t. lxxix. p. 1463.

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occurred, while contractions inward attended slackened movements. An explanation too was hazarded, the substantial truth of which was attested by M. Seeliger's elaborate researches.[1]

It seems then that the star C is merely a satellite to a dark body round which it describes, in 17½ years, a little ellipse with a mean radius of one-fifth of a second. Together this singular pair circuits, or, more probably, is circuited by A B, the invisible disturbing body being the most massive of the system. If this be the case, it is also, of course, the most nearly stationary, and should be regarded as the centre round which the lucent trio revolve—an arrangement hinting to us that the collocation in the same orb, familiar to us in the solar domain, of the functions of rule and light-giving, may, on occasions, be dispensed with. An anti-Copernican system, at any rate, appears to be to some extent exemplified by ζ Cancri. Here a cool, dark globe, clothed possibly with the vegetation appropriate to those strange climes, and plentifully stocked, it may be, with living things, is waited on, for the supply of their needs, by three vagrant suns, the motions of which it controls, while maintaining the dignity of its own comparative rest, or rather of its lesser degree of movement. For the preponderance of this unseen body cannot approach that of a sun over its planets; hence its central position is by no means undisturbed. We must not forget, meantime, that its existence is to some extent hypothetical. Mr. Burnham thought it an evanescent creation of accumulated micrometrical errors;[2] and Professor Frost in 1904 failed to elicit any spectroscopic evidence of the eighteen-year period ascribed to the third star.[3] The close pair (according to Pickering's calculation) possesses nine times the solar emissive power relatively to mass; and all the three visible components show spectra of Sirian quality. Their real differences of magnitude, too, seem to be slight, although at times exaggerated by relative variability. The entire group is

[1] *Sitzungsberichte*, Wien. Bd. lxxxiii. Abth. 2, p. 1018; *Denkschriften*, Munich, Bd. xvii. Abth. 1, 1889; Harzer, *Astr. Nach.* No. 2764; *Observatory*, vol. xii. p. 116.

[2] *Monthly Notices*, April 1891, November 1892; *Astr. and Astrophysics*, vol. xii. p. 872; Seeliger, *ibid.* vol. xiii. p. 802; *Astr. Nach.* No. 3165; *Sitzungsb. Bayer. Akad.* Bd. xxiv. Heft. iii. 1894.

[3] *Astroph. Journ.* vol. xix. p. 355.

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transported through space at the rate of 15″ a century, but its distance from the earth is unknown.

A quadruple system of remarkable type is formed by ζ Ursæ Majoris with three variously related bodies. Besides its spectroscopic and telescopic attendants, the one as agile as the other is sedate in its revolutions, it claims the escort, on its indefinite journey onward, of the fifth-magnitude star Alcor, the two making the combination popularly designated the "Horse and Rider." Since the interval between them is of 11′ 30″, they can easily be distinguished with the naked eye; nevertheless Alcor, totally overlooked by the Greeks, was regarded as a test-object for keen eyesight by the Arabs. Its gradual brightening is thus strongly suggested.[1] The probability that Mizar and Alcor mutually revolve is strong, but not overwhelming; their connection *might* be otherwise explained. If they do, their *annus magnus* must be of enormous, to our ideas of interminable length.

Real quaternary stars are often self-discriminating; their arrangement into two adjacent couples asserts physical connection more strongly than any possible distribution of three stars can do. And in effect, several perspective groups of a single star with a genuine pair, such as δ Equulei, 85 Pegasi, 7 Tauri, and β Delphini, are visibly in course of being dissolved by proper motion, while no "double-double" combination has yet given signs of breaking up.

A representative specimen of the latter class offers itself in ε Lyræ, a star of the fourth magnitude, a little to the north-east of Vega. Exceptionally keen eyes show it as double, and one of the brilliant surprises provided by the heavens for Sir William Herschel was that of finding each component further divisible. The discovery, though beautiful and interesting, was easy; all the four stars can be seen with a good 3-inch telescope. The "preceding" pair, or that which crosses the meridian first, is distinguished as ϵ^1, the "following" pair as ϵ^2 Lyræ; and Flamsteed attached the numbers 4 and 5 to them respectively. The former consists of a fifth and a sixth magnitude star 3″ asunder; the constituent stars of ϵ^2 are nearly equal (5·3 and 5·5 magnitudes), and are set a little closer together (at 2″·45). Their revolu-

[1] Flammarion, *Catalogue*, p. 75.

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tions, too, appear to be performed about twice as quickly as those of the neighbouring couple. From the shifting of their relative situations since 1779 by more than half a right angle, their period may be estimated at about 800 years; while that of ϵ^1 Lyræ is likely to exceed one thousand. The practicability of computing either orbit is still remote.

The small common proper motion (9″ a century) of these bright couples affords positive evidence of their union into one vast system. At their unmeasured, perhaps immeasurable distance, the gap between them of $3\frac{1}{2}'$ may well stand for a chasm costing light itself some months to bridge; yet the stress of their mutual gravity reaches across it, compelling their circulation in orbits so spacious that a single round of them must occupy an era of no insignificant duration, even in the life of a star. The four stars of ϵ Lyræ give a spectrum of the first type, combined, in the leading couple, with a decided cast of yellow. But this is often the case with double stars.

"A miniature of ϵ Lyræ"[1] is offered to our regards in ν Scorpii. This is perhaps the most beautiful quadruple group in the heavens, from the narrow limits within which the brilliant objects composing it are crowded. As a wide double it was noticed by C. Mayer in 1776; after seventy years the smaller star was divided by Mitchel at Cincinnati, and the larger one of fourth magnitude yielded similarly, in 1874, to the insistence of Burnham. Both pairs share with several neighbouring stars a slow drift through space.[2] They are 41″ apart, and have as yet developed no systemic movements.[3]

The sixth-magnitude star 86 Virginis may be said to consist of a double primary with a double satellite at 27″. Full acquaintance with the group was made through Burnham's analysis of one of Struve's "rejected" pairs. Its internal relations will need time to develop.[4] A quaternary combination of peculiar interest was detected by Mr. Innes in 1897.[5] It consists of two close pairs, κ Toucani and Lacaille 353, separated by the wide interval of 5′ 20″; yet, notwithstanding

[1] Flammarion, *Catalogue*, p. 96.
[2] Innes, *Reference Catalogue*, p. 157 A.
[3] Burnham, *Gen. Cat.* p. 149. [4] *Ibid.* p. 128.
[5] *Monthly Notices*, vol. lvii. p. 456; *Ref. Cat.* p. 10 A.

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the antecedent improbability of their connection, it is emphatically asserted by the unanimity of their rapid rate of travel across the sphere.

Eighteen "double-double" star-groups — one (Σ 2435) with a span of no more than 15″—were enumerated by Burnham in 1882,[1] and three have since been added by Hough and Innes.[2] They perhaps exist more numerously than we have as yet any idea of.

A "double-treble" star, so-called by Herschel, has been the subject of numerous successive discoveries. With the slightest optical assistance σ Orionis, a star of 3·7 magnitude, just beneath the middle star in the belt of Orion, separates into two wide and unequal components, each of which was, October 7, 1779, perceived by Herschel to be triple.[3] As usual in such cases the process of resolution was continued, and the assemblage was described by Barlow as "double-quadruple, with two very fine stars between the sets."[4] These last, however, are not unlikely to be mere optical associates. To this intricate group Burnham added a further element of complexity. At Lick, in the autumn of 1888, he found its chief member to be formed of a fourth and a sixth magnitude star, a quarter of a second apart, and yielding, after ten years, signs of mutual circulation.[5] The disclosure, like some others, raised a question as to the point where stellar subdivision can really be said to cease. That it is not where visual limitations interfere with our recognition of it was emphatically reasserted in 1904 by Professors Frost and Adams's spectroscopic discovery that the primary of Burnham's pair is intimately, though invisibly coupled with an obscure, massive body.

The essential character of σ Orionis is that of being made up of two distinct, yet evidently connected *knots* of stars, and the same knot (Σ 762)[6] contains all the four brightest components. These differ, and perhaps vary in colour, and their influence may be assumed to predominate in this remarkable system.

[1] *Observatory*, vol. iv. p. 176.
[2] *Astr. Nach.* No. 2778; *Monthly Notices*, vol. lvii. p. 456.
[3] *Phil. Trans.* vol. lxxii. p. 124.
[4] Smyth, *Cycle of Cel. Objects*, ed. 1881, p. 156.
[5] *Astr. Nach.* No. 2875; *Gen. Cat.* p. 68.
[6] Struve, *Mens. Microm.* pp. 149, 245.

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The multiple star 45 Leporis is organised on a plan less definite than that governing the structure of σ Orionis. Just visible to the naked eye, it consists of four principal and five subordinate members, successively discovered by Sir John Herschel and Burnham.[1] One of the stars, of eighth magnitude, stands out through its ruddy colour from its white companions.[2] The entire group of nine objects covers an extent of 125″.

The nebular relations of double and multiple stars were noticed with surprise by Sir John Herschel at the outset of his career.[3] Although admitting without hesitation their physical character, he was without the means of establishing it since made available, and could support his conviction only by the utter improbability of such collocations as he pointed out being fortuitous. Thus, a close, minute stellar couple is planted at the exact centre of a faint round nebula in Leo (New Gen. Cat., 3230); and the same kind of coincidence recurs twice in the southern constellation Dorado (N.G.C. 1732, 1951). Two pairs in Sagittarius, each set in the midst of a nebula (N.G.C. 6589, 6590) may from their contiguity be suspected to constitute one system; and two ninth-magnitude stars at 15″, marking very nearly the foci of an elliptical nebula in the same region (N.G.C. 6595), are certainly not accidentally projected upon it. "One of the most curious objects in the heavens" (according to Sir John Herschel),[4] is a trio of stars arranged in a minute equilateral triangle, relieved upon a shield of milky light (N.G.C. 1931); and its singularity was enhanced by the duplication, under Burnham's gaze in 1891, of one member of the combination.[5] By the same observer, again, an eighth-magnitude star right at the heart of a round nebula in Monoceros (N.G.C. 2182) was divided, also in 1891, into a delicate pair,[6] the remeasurement of which after twelve years, by Professor Aitken, gave evidence of slow circulation. Of circulation, we remember with surprise, conducted in a nebulous medium, and therefore presumably

[1] Burnham, *Memoirs R. Astr. Soc.* vol. xliv. p. 238; *Astr. Nach.* No. 2062; *Observatory*, vol. iv. p. 177; *Gen. Cat.* p. 68.

[2] G. Knott, *Observatory*, vol. iv. pp. 184, 212.

[3] *Memoirs R. Astr. Soc.* vol. vi. p. 78.

[4] *Ibid.* vol. iii. p. 54.

[5] *Gen. Cat.* p. 65.

[6] *Ibid.* p. 75.

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impeded. But if so, the system could not be a permanent one, and a temporary star should result from its collapse. The difficulty is intensified by the consideration of many other still more noteworthy instances of the association of composite stars with nebulæ. The whole framework of the great nebulous structure in the sword of Orion seems to rest upon the stellar group designated θ, or rather θ^1 Orionis; for there is a second θ not far off, itself a wide double star; and the two together form, to the eye, one diffuse object, singly catalogued by Ptolemy, Tycho Brahe, and Hevelius. But it is with θ^1 exclusively that we are at present concerned.

On the very slightest telescopic persuasion, it allows itself to be seen as quadruple. The four stars into which it divides are severally of fifth, sixth, seventh, and eighth magnitudes, the greatest interval between any two of them not exceeding 21″. None of them is in visible subordination to any other; they stand, it might be said, on an equal footing, at the four corners of a rudely quadrilateral figure, or "trapezium." They maintain their places, too, both absolute and relative, with singular rigidity. After two and a half centuries of observation, no shifting of them can be detected. They are hence likely to be at a prodigious distance from the earth.

The rule that such groups seem more crowded as they are better seen, has not been infringed here. A fifth star of the eleventh magnitude was added to the company by Struve, November 11, 1826, and a sixth, still fainter, by Sir John Herschel, February 13, 1830. Both of these, though closely adjacent, each to one of the larger stars, share their apparent immobility.[1] Variability in light has often been ascribed, and as often denied to them. Burnham's experience is against it; yet the curious fact that Robert Hooke saw the fifth star in 1664 with a non-achromatic three and a half inch telescope,[2] is strongly indicative of temporary brightening; and M. Comas Solà was convinced that the sixth star was shining with unusual lustre when he observed it, after an interval of some months, on November 10, 1901.[3] Individual and

[1] Burnham's measures seem decisive on this point. See *Memoirs R. Astr Soc.* vols. xliv. pp. 203, 237; xlvii. p. 244; *Monthly Notices*, vol. xlix. p. 257 *Publ. Lick Observatory*, vol. ii. p. 46.

[2] *Micrographia*, p. 242.

[3] *Astr. Nach.* No. 3751.

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atmospheric conditions are, however, largely concerned in such persuasions; when they conspire favourably, it is well ascertained that all six of the trapezium-stars can be made out with achromatics or reflectors three to four inches in aperture.[1] Hooke's observation can scarcely then be said to demonstrate change.

Further members of this group have, at various times, been half-seen, half-surmised; but their existence, always problematical, has been disproved through the application of the Lick thirty-six inch; for the three new stars perceived from Mount Hamilton by Alvan G. Clark and Barnard could certainly not have been detected with any less powerful instrument. Two of them lie within the trapezium; the third, a double star of extraordinary minuteness and difficulty,

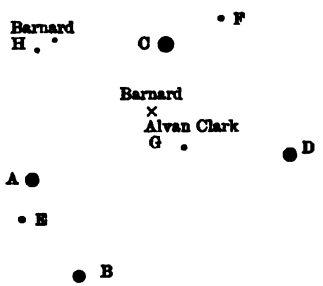

FIG. 27.—Stars of the Trapezium.

just outside it.[2] Their positions are shown on the accompanying diagram (Fig. 27) where G and H represent two of the recently discovered stars, the third, as an imperfectly determined object, being provisionally marked with a cross.

The fact that the leading star in the trapezium has proved to be a spectroscopic binary is not the less astonishing because of its congruity with much that had previously been learned. Sir William and Lady Huggins recorded in 1897[3] the first signs of its duplicity; they were assured and defined by the Yerkes measures in 1904.[4] Its nature is moreover shared, and attested through a far larger variation of radial

[1] Webb, *Cel. Objects*, p. 367.
[2] Burnham, *Monthly Notices*, vol. xlix. p. 352; *Astr. Nach.* No. 2930.
[3] *Astroph. Journ.* vol. vi. p. 322.
[4] Frost and Adams, *ibid.* vol. xix. p. 153.

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speed, by θ^2 Orionis, which crosses the meridian six seconds later than the septuple object to the west. Half a degree to the south lies ι Orionis, a triple star immersed in an outlying shred of the Sword-handle formation. Here again visual has been followed up by spectroscopic resolution. The diffuse dark lines in the prismatic light of ι Orionis oscillate to an extent indicating to and fro velocities of 60 kilometres (37½ miles) a second. And by similar tokens, the nebulous stars S Monocerotis, 57 Cygni, and σ Scorpii are known to be swiftly circulating couples. The investigation of systems so singularly circumstanced will doubtless serve to elucidate the relations of the glimmering fields of space to masses of matter traversing them. Should they appear to slip through unopposed, our ideas as to the essential properties of material substance will have to be considerably modified.

In one other great nebula besides the Orion structure a multiple star seems dominant. The nuclear group in the trifid nebula (N.G.C. 6514) consists of a close quartette covering an angular extent of only 19″, with two extremely faint additional stars discovered by Professors Langley and Holden. Complete apparent fixity characterises the arrangement.

The frequent association of compound stars with nebulæ is no mere isolated fact. For they pass by insensible degrees into star-clusters, the nebulous affinities of which have been, in many cases, established with the aid of photography. The conjecture is even plausible that the formation of a multiple star in a great nebula represents the initial stage of the development from it of a crowded clustre, minor nebulæ giving rise to lesser groups; and if objects of the kind have not yet, so to speak, been turned out of the workshop, it is no wonder that fragments of their raw material still cling round them. Compositeness of structure may thus measure primitiveness of condition, illustrating, though to us dimly, the sequence of Divinely decreed changes by which cosmical order is gradually more and more fully disengaging itself from the "loud misrule" of chaos.

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CHAPTER XVI

THE EVOLUTION OF MULTIPLE STARS

STARS joined together in systems peremptorily assert a common origin. Their companionship is not due to chance. Bodies moving independently in space may circuit one another in a hyperbolic orbit; but the event should be unique. They can never meet again. Permanent capture is practically out of the question. The intervention of a third body would be required to bring it about, and the third body should be critically situated, and of enormous mass to produce the necessary amount of retardation. The possibility of a casual approach having led to an indissoluble union is indeed too remote to be worth counting. Multiple stars, we may rest assured, were such potentially from the first.

Yet the manner of their origin remained long an impenetrable mystery. Clearly, it belonged to the regular order of sidereal arrangements; and quite as clearly, it differed *toto coelo* from the series of operations by which the planetary system had come into existence. Nor could any reason for the divergence be assigned until Dr. See published, in 1893, his researches on the part played by tidal friction in moulding the relations of double stars. Based on Professor Darwin's memorable inquiries into the antique history of the earth and moon, they followed a line essentially original. No attempt had previously been made to trace the consequences in stellar systems of a mode of action known to have been powerfully effective within the narrow precincts of the lunar sphere. Yet, since it gains efficacy as the ratio between the masses submitted to it approximates to equality, it should reach a maximum of influence in modifying the relations of co-

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ordinate bodies such as double stars. Tidal friction is, in Dr. See's words, "a necessary adjunct of gravitation wherever systems of fluid bodies exist in a state of relative motion; it is a physical agency as universal as gravitation itself, operating more or less powerfully in all the systems of the universe."[1]

The key to the enigma of double-star development was given by the high eccentricities of their orbits. Two bodies revolving very close together are not only pushed asunder by tidal reaction, but are forced to retreat along tracks that become elongated as they widen. The process is terminable after an indefinite lapse of time; and is even theoretically reversible, though to an almost evanescent degree. What we just now have to do with, however, are the direct workings of a cause, satisfactorily shown to be adequate to the effects assigned to it. If this be so, telescopic star-pairs set forth on their careers as spectroscopic binaries; while spectroscopic binaries must, through the influence of tidal friction in widening their paths, be steadily growing into visual couples. One class is complementary to the other, and Dr. See's hypothesis obtains fresh confirmation from each additional discovery of a star with variable radial motion.

Moreover, these excessively close systems are strongly marked by signs of progressive change. Some appear to be still inchoate. The eventual stars are intimated by certain phenomena of their light-changes to be perhaps as yet undivided. Connected, it is thought, by a surviving ligament, they revolve as a dumb-bell might, pivoted on its neck, and aptly illustrate the "apioidal" forms dealt with in the formulæ of Poincaré and Darwin. From the rupture of a spinning "dumb-bell," then, to stately binaries in secular revolution, a virtually unbroken series of instances can be traced; and that the advance is really a development, is a fairly irresistible conclusion. A set of specimens presenting gradual modifications of a given type proclaims of itself a transforming agency; and double stars exhibit, not only all the linked instances that could be expected, but the requisite agency for producing them ready at hand in the grinding and modelling power of tidal friction.

[1] *Astr. and Astrophysics*, vol. xii. p. 290.

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The theory of double-star evolution through its exceptional efficacy in embryonic stellar systems is thus, at first sight, strongly recommended. It must be true to some extent. But it has limitations and qualifications which should not be overlooked. The dynamical and physical histories of double stars are intimately connected. Their relative masses and densities, their spectral congruities or divergencies, their colour and brightness, are so many items of evidence as to the course of their companionship, and the destiny awaiting them. Comparative inquiries are indeed especially difficult for objects in many cases barely separable in the sky, yet they have been set on foot; and the few facts so far collected are valuable, both in themselves, and as an earnest of a fuller harvest. Meantime, they seem to warrant one or two provisional generalisations. The first is, that contrasted pairs of yellow and blue tints are formed each of a solar and Sirian star, the lesser component showing the more primitive spectrum. Since, however, their revolutions are of inordinate slowness, their mass-relations cannot be apportioned. It is only permissible to say that if satellite-stars resemble in constitution solitary stars of similar light-quality, their brilliancy must exceed the proportion of their mass. Their gravitative disparity should, in this case, largely outmeasure their visible inequality.

An opposite rule seems to apply where the secondary star is of a roseate or purplish hue. It is founded, indeed, upon only two ascertained instances; yet they do not appear to be exceptional. The companion of 70 Ophiuchi, while of less than one-fourth the brightness of its primary, quadruples its mass. Admitting it to be of the same density, it gives eleven times less light per square mile of photospheric surface. And for the analogous pair, η Cassiopeiæ, the ratio is ten to one. The lesser luminary shines with one-tenth the areal brilliancy of the primary, equal densities being again assumed. Unfortunately, the rays of these heavy satellites have not been separately analysed; so that, in the few cases where spectral distinctions are on record, nothing is known as to relative mass; and where relative masses have been determined, differences in light-quality are undiscriminated. An exception is furnished by α Centauri, the components of which

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are thoroughly individualised. But they show no heterogeneity of colour or spectrum. One is a deeper yellow than the other, simply because its absorption is stronger than, though similar to that of its comrade. Binary systems undoubtedly offer the most promising field for investigating the stages of stellar development. Their relative antiquity, to begin with, can be roughly estimated; for there is good reason to suppose the closest and swiftest pairs to be in general the most primitive. Further, the components of each are necessarily of the same age. Whatever spectral differences they present cannot then be set down to the exclusive account of time. They are either aboriginal, or have supervened as the result of innate diversities. Thus, bodies unequal in mass are unlikely to develop at the same rate. The long-accepted opinion was that it should be slow in proportion to the quantity of matter contained in each globe. Sir William and Lady Huggins, however, suggested in 1897 doubts on this point.[1] They indicated the probability that a high gravitational constant might hasten the transition from a Sirian to a solar spectrum; and the phenomena of double stars seem expressly adapted to serve as a criterion whether this is so or not. A decisive conclusion could be drawn from a comparison of the masses of such a chromatic pair as ϵ Boötis; but the possibility of instituting it is in the dim future.

Something, on the other hand, may be learned from the great spectroscopic binary Capella concerning the influence of massiveness upon spectral history. If the plane of its revolutions passes through the earth, the attractive power residing in the system is more than twice that of the sun; and this minimum estimate should be increased eight-fold to correspond with an orbital inclination of 60° to the line of sight. Now the star is enormously brilliant. It has a measured parallax, and at its distance, our sun would appear 102 times fainter. Assuming the components of the binary to be equal globes, of solar density and intrinsic lustre, each should possess the mass of 363 suns. Their mutual attraction, in other words, should exceed 726 times the gravitational pull exerted on the planets. Nevertheless, the highest value that can plausibly be assigned to their joint mass is twenty times that of the sun. The

[1] *Astroph. Journ.* vol. vi. p. 326.

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tremendous discrepancy thus made apparent obliges us to suppose that Capella, while spectroscopically almost a replica of the sun, is an orb far less condensed and more luminous. It then evidently became invested at a much earlier stage of cooling, with a reversing layer similarly composed to that producing the Fraunhofer lines. Further experience must decide whether giant suns of this type are invariably more tenuous than their light would lead us to expect, or whether Capella is in this respect peculiar. Its example serves at least to give an idea of the modes of evolutionary inquiry rendered feasible by the study of binary systems.

Inequality between mass and light is pushed to the last extreme in the obscure, though strongly attractive attendants of many lustrously white stars. A large number of such incongruous couples have been discovered spectrographically, and the enigma they present finds no ready solution. Clearly, disparate loss of energy by radiation will not reasonably explain the contrast of their present state. Rather, some profound diversity of constitution must be supposed to have brought it about. The brilliancy of stellar photospheres essentially depends upon the activity of interior circulatory processes. These are perhaps, in abnormally dark globes, prematurely retarded or arrested. But the how? and why? evade divinatory efforts.

From dwelling on the origin of binary stars, our thoughts insensibly range beyond them to larger combinations. Revolving couples very often form only part of an extended system. Is it conceivable that such varied aggregations were fashioned throughout by the same kind of influence? Was tidal friction the factotum in all their developmental changes? To affirm it would be perilous. There is no warrant for ascribing an iron consistency to creative methods. In the planetary system, at any rate, they seem to have been considerably varied. Professor Darwin has virtually demonstrated that lunar-terrestrial relations lay apart. No other member of the solar family could have originated by fission, as the moon presumably did, or raised a tidal wave of overruling magnitude on the still plastic surface of its primary. Hence, uniformity in the processes of cosmogony need not be taken for granted. We may, for example, reasonably admit that the

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close pair in ζ Ursæ Majoris divided at close quarters similarly to the earth and moon, without extending the inference to the telescopic companion of the same star; still less to Alcor, its distant fellow-passenger through space. Each case should be considered on its merits, without prepossession in favour of harmonising the results. Indeed, the long series of operations traced out by Dr. See is scarcely capable of being duplicated. Through over-rapid spinning, a fluid globe may split asunder once; but a repetition of the event is virtually precluded by the very consequences of the first disruption. For the newborn satellite exerts, by the drag of the tidal wave it raises on its primary, a powerful retardative influence on its rotation; the speed of which is most unlikely to reach a second time the pitch needed for instability; and the satellite itself is under the same prohibition. Multiple stars, then, cannot, so far as we are able to judge, have been formed by successive subdivisions of one parent mass. In stellar systems, as in the solar system, many degrees of relationship are distinguishable. Groups in loose mutual connection may have originated contemporaneously in different sections of the same nebula. Binaries of co-ordinate rank are doubtless frequently included in a single complex mechanism. This species of remote kinship is forcibly suggested by the movements of ξ Scorpii, one of the few triple stars, all the members of which are in visible revolution. Yet not in the same sense. The close pair circulates directly, the third, more distant companion (as already stated), in a retrograde direction. The wide divergence thus probably indicated of the two orbital planes betokens unmistakably a remarkable dissimilarity in the conditions under which the near and the remote satellites respectively took their origin. A more intimate acquaintance with such systems will perhaps show the case of ξ Scorpii to be typical; it is assuredly most significant. Again, the six stars forming the Orion trapezium are, beyond cavil, a physical group, in immediate genetic connection; yet it would be extravagant to suppose one the parent of the others. Only the dark body circulating contiguously to the brightest of the sextett can be regarded as its proper offspring; the rest claim an independent footing. We can conceive them as having condensed from distinct knots in one vast nebulous structure

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impressed with a slowly wheeling movement. We cannot conceive them as thrown off one after another by one swiftly rotating globe. The same might be said of the quadruple system ϵ Lyræ, and of many more.

The more attentively cosmic processes are studied, the more various they appear. Thus, comets can be clearly seen to have originated differently from planets, and some planets differently from others; while our own satellite struck out a line for itself. The large consonances of the solar system subsist amid diversity of detail, attesting strong individualities of history and status. And such diversity has its fullest scope among the stars. It is much if we can catch glimpses of partial truth in meditating on their evolutional order; the profundities of its meaning, and the intricacies of its roots in the past, and ramifications into the future baffle our scrutinising efforts.

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CHAPTER XVII

THE PLEIADES

FROM multiple stars the transition is easy to star-clusters. These seem to embody completely the idea contained in germ in the former class of objects. They are collections, often on the grandest scale, of sunlike bodies small and large, united in origin and history, acted upon by identical forces, tending towards closely related ends. The manner and measure of their aggregation, however, vary widely, and with them the cogency of the evidence as to their organic oneness. There are innumerable cases in which it absolutely excludes doubt; there are some in which it is rather persuasive than convincing. It is not then always easy to distinguish between a casual "sprinkle" of stars and a genuine cluster. Nor can the movement-test, by which so many physical have been discriminated from optical double-stars, be here applied. Internal displacements of a circulatory character have not yet become apparent in any cluster, and there is only one with an ascertained common proper motion.

This is the immemorial group of the Pleiades, famous in legend, and instructive, above all others, to exact inquirers—the meeting-place in the skies of mythology and science. The vivid and picturesque aspect of these stars riveted, from the earliest ages, the attention of mankind; a peculiar sacredness attached to them, and their concern with human destinies was believed to be intimate and direct. Out of the dim reveries about them of untutored races, issued their association with the seven beneficent sky-spirits of the Vedas and the Zendavesta,[1] and the location among them of the

[1] Bunsen, *Die Pleiaden und der Thierkreis* P. 434.

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centre of the universe and the abode of the Deity, of which the tradition is still preserved by the Berbers and Dyaks.[1] With November, the "Pleiad-month," many primitive people began their year;[2] on the day of the midnight-culmination of the Pleiades, 17th November, no petition was presented in vain to the ancient kings of Persia;[3] and the same event gave the signal at Busiris for the commencement of the feast of Isis, and regulated less immediately the celebration connected with the fifty-two year cycle of the Mexicans. Savage Australian tribes to this day dance in honour of the "Seven Stars," because "they are very good to the black fellows." The Abipones of Paraguay regard them with pride as their ancestors.[4] Elsewhere, the origin of fire and the knowledge of rice-culture are traced to them. They are the "hoeing-stars" of South Africa,[5] take the place of a farming-calendar to the Solomon Islanders, and their last visible rising after sunset is, or has been celebrated with rejoicings all over the southern hemisphere, as betokening the "waking-up time" to agricultural activity.

To the Greeks of Hesiod's age their "heliacal rising" (the first visible before sunrise) announced, each May, the opening of the season for navigation; and their name thus came to be interpreted (from *pleîn*, to sail), the "sailing-stars." But this etymology was doubtless—like the derivation of "elf" and "goblin" from *Guelf* and *Ghibelline*—an afterthought; and it may be confidently maintained that the word "Pleiades," bearing like its Arabic and Hebrew equivalents, the essential signification of a "cluster," came from the Greek *pleîones*, many, or *pleiôs*, full.[6] It was represented in Latin by "Vergiliæ" (from *ver*, spring), a designation possibly commemorative of the ancient coincidence of the stars with the vernal equinox. They were, moreover, chosen about the same epoch—say 2700 B.C.—by the Hindus to mark the first lunar

[1] Haliburton, *Nature*, vol. xxv. pp. 100, 317; Van Sandiak, *L'Astronomie*, t. iv. p. 367.

[2] Haliburton, *Festival of the Dead*, p. 46.

[3] *Ibid.* p. 13.

[4] Lubbock, *Origin of Civilisation*, p. 316, 4th ed.

[5] J. Hammond Tooke, in an interesting paper read in January 1889 before the S. African Philosophical Society.

[6] *Nature*, vol. xxxv. p. 608.

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mansion, called "Krittika," general of the celestial armies;[1] and long occupied the same post in Chaldea under the title "Thurayya," the crowd.[2]

The similarity of the traditions respecting the swarm of celestial "fireflies,"

Quæ septem dici sex tamen esse solent,

is as surprising as their universality. That they "were seven who now are six," is asserted by almost all the nations of the earth, from Japan to Nigritia, and variants of the classical story of the "lost Pleiad" are still repeated by sable legend-mongers in Victoria and Western Australia, by "head-hunters" in Borneo, by fetish-worshippers amid the mangrove-swamps of the Gold Coast. An impression thus widely diffused must either have spread from a common source or originated in an obvious fact, and it is at least possible that the veiled face of the seventh Atlantid may typify a real loss of light in a pre-historically conspicuous star. Some members of the collection are at present, there is little doubt, slightly or slowly variable,[3] and progressive tendencies of the kind are in more than one case suggested to be present. Thus Alcyone, the chief of the collection, now of the third magnitude, and just twice as bright as the brightest of its companions, was either not one of the four Pleiades observed by Ptolemy, or was then much fainter than it has been from Tycho Brahe's time to our own. So at least Francis Baily concluded from a careful examination of the records,[4] and he knew better than most men how large an allowance has to be made for ancient inaccuracy. Al Sûfi, too, the competent reviser of Ptolemy's observations, expressly states that the Alexandrian quartette appeared to him, in the tenth century, the most lustrous among the Pleiades.[5] Yet none of them can be identified with the present *lucida*. A literal explanation of the old legend may

[1] R. H. Allen, *Star Names and their Meanings*, p. 392.

[2] Weber, *Indische Studien*, Bd. x. p. 215.

[3] C. Wolf, *Annales de l'Observatoire de Paris*, t. xiv. ii. p. 26; Lindemann, *Mémoires de l'Acad.*, St. Pétersbourg, t. xxxii. vii. Sér. No. 6, p. 29; Vogel, *Potsdam Report*, 1899.

[4] *Memoirs R. Astr. Soc.* vol. xiii. p. 9.

[5] Schjellerup, *Description des Étoiles*, p. 132; Flammarion, *Les Étoiles*, p. 294.

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hence be feasible, and Professor Pickering's suggested identification of Pleione with the missing Atlantid has much to recommend it.[1] The display by this star of a gaseous spectrum resembling that of P Cygni countenances the view that, like P Cygni, it formerly shone with temporary or intermittent brilliancy. It is now of 5·4 magnitude, or just twice as bright as it was, by Argelander's estimate, fifty years ago.

The five stars ordinarily visible besides Alcyone (see Plate I. Frontispiece) are Electra and Atlas, each fluctuating slightly above and below 3·8 magnitude; Maia, now of the fourth, or one magnitude fainter than Alcyone; Merope and Taygeta, the inferiors of Maia by respectively a quarter and a half magnitude. Celæno, the seventh or concealed star, gives only about one-third the light of Taygeta.

Yet it can be seen with many others, under favourable circumstances. Maestlin, the tutor of Kepler, perceived fourteen, and mapped eleven Pleiades previously to the invention of the telescope; Carrington and Denning counted fourteen,[2] Miss Airy marked the places of twelve with the naked eye.[3] The faintest of these fell but little short of the sixth, and there are twenty-three Pleiades down to the seventh magnitude,[4] each of which (with perhaps one or two exceptions) might be separately visible in a transparent sky or from an elevated station. But their crowded condition makes this impossible, and gives rise rather to the effect described by Kazwini in the thirteenth century, of "six bright stars with a number of dusky ones between."[5]

With the use and increase of telescopic powers, the populousness of the cluster has been amazingly increased. An object-glass scarcely exceeding two inches diameter showed Robert Hooke in 1664 seventy-eight Pleiades,[6] and Michell's conjecture, in 1767, that there might be more than a thousand of them,[7] has been superabundantly verified by the results of modern labours. Over an area about Alcyone measuring

[1] *Astr. Nach.* No. 2934.
[2] Webb, *Cel. Objects*, p. 393.
[3] *Monthly Notices*, vol. xxiii. p. 175.
[4] *Harvard Annals*, vol. xiv. pt. ii. p. 398; cf. Müller and Kempf, *Astr. Nach.* No. 3587.
[5] Ideler, *Sternnamen*, p. 147.
[6] *Micrographia*, p. 241.
[7] *Phil. Trans.* vol. lvii. p. 259.

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$135' \times 90'$ M. Wolf catalogued, at the Paris Observatory in 1876, 625 stars to the fourteenth magnitude; on the MM. Henry's sensitive plates, in 1885, 1421 made their appearance in a smaller space, and the number was brought up to 2326 by exposures of four hours in November and December 1887. The faintest objects thus registered were probably of about the sixteenth photometric magnitude.

How many of them really belong to the group, and how many are referred to it by perspective, can be determined with the help of time and patience. As regards some of the better known stars, the process of discrimination has already begun.

Bessel's measurements of the places, relative to Alcyone, of 52 Pleiades,[1] executed with the Königsberg heliometer during the twelve years from 1829 to 1841, furnished a starting-point for investigations of their internal movements. The upshot of the first effective comparisons was to exhibit these as null. From a collodion-print of the cluster taken by Rutherfurd of New York in 1865, Dr. Gould redetermined nearly all Bessel's stars with such accuracy as to make it certain that no appreciable *interstitial* shiftings had occurred in the course of a quarter of a century;[2] and his conclusion was, through additional photographic comparisons of ten of the same stars, extended by Professor Jacoby to the year 1900.[3]

Now this seeming rigidity implied a great deal. For the point of origin of the measures in question is not immovably fixed in the sky. The chief Atlantid has a secular proper motion (according to Newcomb) of $6''$, the possession of which in common by the whole stellar band virtually demonstrated their effectual union. Where one among many objects is ascertained to be moving, relative fixity can only mean that all drift together; and so the unique phenomenon was brought to light of the transport in block across the sphere of some scores or hundreds of congregated suns. Even if the whole of this apparent displacement should prove to be as it were reflected from the solar advance, its significance of physical kinship among the objects affected by it would be nowise impaired. For an identical parallactic shift would equally

[1] *Astr. Nach.* No. 430. [2] *Observatory*, vol. ii. p. 16.
[3] *Astroph. Journ.* vol. xiii. p. 56.

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suffice to locate them in the same region of space under the immediate influence of their constraining mutual gravity.

The establishment of a general unanimity of movement among the Pleiades was the first step towards investigating their relations; the next was to seek evidence of systematic change. This has still to be found; its highly recondite nature has been rendered unmistakable by the labours of Wolf,[1] Pritchard,[2] and Elkin.[3] Displacements within the cluster, though necessarily in progress, are barely nascent. Something, however, has been done towards its analysis, as the result of Dr. Elkin's work at Yale College in 1884-85.

Leaving nothing to be desired in the way of skill and care, it was the more strictly comparable with Bessel's from having been executed, like his, with a heliometer, one of about seven inches aperture, completed in 1882 by the Messrs. Repsold of Hamburg. Sixty-nine stars, down to 9·2 magnitude, were included in the survey, only one of Bessel's being omitted, while seventeen were added from the Bonn Durchmusterung. The close agreement, on the whole, between the places determined, after an interval of forty-five years, at Königsberg and Yale, lent importance to some minute discrepancies, the most considerable of which intimated the probability that six of the objects on Bessel's list were only apparent members of the cluster.[4] They should probably be regarded as pseudo-Pleiades, intruders into a company from which they will eventually be expelled through the cumulative effects of incompatible movements. Exempt from the influence of the current bearing Alcyone and its true associates slowly towards the south-south-east, they remain almost absolutely stationary, and are accordingly in course of being left behind. Recent counts by Pickering[5] and Stratonoff[6] make it fairly certain that the majority of the small stars within the area of the Pleiades will be left behind with them. The ground for this

[1] *Annales de l'Observatoire*, t. xiv. ii.; *Comptes Rendus*, t. lxxxi. p. 6.

[2] *Monthly Notices*, vol. xliv. p. 357.

[3] *Trans. Yale College Observatory*, vol. i. pt. i. 1887. Pt. viii. contains results of a second triangulation by M. F. Smith in 1900-2.

[4] Dr. Elkin expressed this view with considerable reserve as regards four of the six stars. Cf. his revised conclusions, *Trans. Yale Coll. Observatory*, vol. i. pt. vii. p. 356, 1904.

[5] *Harvard Circular*, No. 17.

[6] *Astr. Nach.* No. 3441.

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inference is that they are less densely strewn than the multitudinous stars in the adjacent sky. The true *glomerabile sidus* is then formed of brighter objects, the number of which, though still unknown, can be ascertained after a moderate lapse of time by renewed photographic comparisons.

The proper motion of Alcyone reverses, with approximate accuracy, the direction of the sun's progress through space. It may hence be regarded as parallactic, that is, transferred by perspective from our own. If this be so, the distance between Alcyone and the earth can be calculated, given the direction and velocity of the sun's translation. Now we know that the sun is travelling towards a point in the constellation Lyra at the rate of about twelve miles a second. On this showing, the Pleiades are so remote that their light takes 190 years to reach us (parallax = 0″·017). Nor is the estimate likely to be materially diminished.

Our own sun, thus far away, would shrink to a star of 8·6 magnitude. There can be little doubt, in fact, that it is surpassed in brilliancy by fifty to sixty of the Pleiades. And it must be, in some cases, very greatly surpassed; by Alcyone 170, by Electra 83, by Maia about 70 times. Sirius itself takes a subordinate rank when compared with the five most brilliant members of a group, the real magnificence of which we can thus in some degree apprehend.

The scale of its construction is no less imposing. No judgment can of course be formed as to the interval of space separating any two of the stars belonging to it. All of them are seen projected indiscriminately upon the same plane, without regard to the directions in which they lie one from the other. The line joining Maia, for instance, with Alcyone, may be foreshortened to any extent, or not at all. No criterion is at hand which we can apply. Of the dimensions, however, of the cluster as a whole, some notion can be gathered. For its shape—irrespectively of some outlying streams of small stars—may be taken to be rudely globular; and since a circle described from Alcyone as a centre with a radius of 48′, includes all the principal stars, sixty of Elkin's sixty-nine, fifty-two of Bessel's fifty-three falling within it, the apparent diameter of the denser part of the aggregation cannot differ much from 96′. But the proportion of the

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radius to the distance of a globe is known from elementary trigonometry, and here comes out (in round numbers) as one to seventy-one; so that the bodies situated close to its surface are seventy-one times nearer to their central luminary than their central luminary is to us. If they revolve round it, it is at an interval exceeding fifteen billion miles, costing light not far from three years to cross; and the period of their circulation may well be reckoned by millions of years. Upon these dependent orbs, Alcyone shines with sixty times the lustre of Sirius in terrestrial skies; yet the presence of 130,000 Alcyones would only just compensate for the withdrawal of even such a diminished sun as brightens the firmament of Neptune. From stars more centrally placed, the chief of the cluster doubtless appears a veritable sun, although it may not be to all the primary light-giver. An assemblage like the Pleiades distributed round our sun would extend *compactly* three-quarters of the way to *a* Centauri, its feelers and appendages indefinitely farther. Hence there would be ample room in it for secondary systems and particular associations of luminous bodies. And, in point of fact, the actual cluster contains several of Burnham's close double stars, one certainly,[1] all presumably in mutual revolution, to say nothing of the doubtful companion of Atlas which, distinctly visible only once to Struve in 1827, gave nevertheless some sign of its presence during an occultation by the moon, January 6, 1876.[2]

The discovery of Maia as a spectroscopic binary suggests an indefinite range of hidden complexities in the mechanism of the cluster. It ensued in the course of a research on the radial velocities of the six leading Pleiades, carried out by Mr. Walter Adams with the Bruce spectrograph of the Yerkes Observatory in 1903-4.[3] The diffuseness of the spectral lines in these stars impaired the precision of most of the determinations; but Maia offered more facilities than its companions; and the variation of its speed to the extent of about eighteen miles a second seems indisputable. The period of its revolutions has still to be assigned. The other five stars all proved to be receding from the sun at rates corresponding

[1] *Astr. Nach.* No. 3047. [2] *Ibid.* No. 2074.
[3] *Astroph. Journ.* vol. xix. p. 338.

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fairly well with the sun's celerity of withdrawal from them. That is to say, no evidence of individual motion (unless possibly in the case of Taygeta) was elicited from them. Spectroscopic measures are then no more immediately hopeful than micrometrical measures[1] for obtaining a clue to the dynamical condition of this marvellous star-group.

A spectrum of helium type characterises its genuine members. A simultaneous spectrographic impression obtained by Professor Pickering from close upon forty of these stars, January 26, 1886, demonstrated the nearly identical quality of their light, and furnished "strong confirmation of their common origin."[2] Only in two cases, a stronger "K line" recorded itself than such light ordinarily includes, and the divergence was, in one of the two, both accentuated and explained by diversity of motion. The star in question (*s* Pleiadum) has been already signalised as an incipient fugitive from the group to which it never truly appertained.

The stars of the Pleiades, while shining with so poignant a lustre as to make the sky-ground they are relieved upon show to the eye as blacker than elsewhere, are in reality wrapped and entangled in an immense cosmical cloud. Some indications to this effect caught by optical means have been autographically amplified to so surprising an extent that the discovery of the nebulous condition of the Pleiades ranks among the most important achievements of celestial photography.

The "Merope nebula" was compared by M. Tempel to a stain of breath upon a mirror. Discovered by him at Venice, October 19, 1859, it envelops and stretches back in cometary shape from the star to which it is attached, covering a space of about 35′ by 20′.[3] But this large size only makes its perception more difficult, by impairing the effect of contrast with the surrounding sky. High magnifying powers (which imply narrow fields of view), render it on this account completely invisible, and a haze so slight as to permit the observation of stars of thirteenth or fourteenth magnitude suffices

[1] Elkin, *Trans. Yale College Observatory*, vol. i. p. 101.

[2] *Memoirs Amer. Acad.* vol. xi. p. 215; *Harvard Annals*, vol. xxvi. pt. ii. p. 262, where the spectra of ninety-one members of the group are specifically recorded.

[3] *Astr. Nach.* No. 1290; *Monthly Notices*, vol. xl. p. 622.

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to obliterate it. This evasiveness suggested variability; but Tempel's contrary opinion has been fully justified.

The idea was entertained both by Goldschmidt[1] and Wolf, that the filmy veil flung round Merope was but a fragment of a larger whole; and as time went on, glimpses were snatched of misty shreds and patches in connection with other members of the group. Alcyone appeared to Searle at Harvard College, November 21, 1875, surrounded by whitish light;[2] the effusion about Merope, evidently to Schiaparelli in 1875,[3] and to Maxwell Hall in 1880, reached Electra and even Celæno;[4] while a remarkable view afforded to the late Dr. Common by his three-foot reflector, February 3, 1880,[5] of three feebly luminous blotches between Merope and Alcyone, prompted his comment that "there is a great deal yet to be settled as to the extent and number of the nebulæ in this cluster."

Its import, however, became apparent only when photography was brought to bear upon the subject. The first nebula discovered by the new method was a small spiral appendage to the star Maia, which printed itself on plates exposed by the MM. Henry, each during three hours, in December 1885.[6] Only the accumulating faculty of the "chemical retina" could have revealed the presence of an object so excessively faint in a telescopic sense; but what is known to exist is, by that alone, rendered more than half visible, and the Maia nebula was accordingly discerned, February 5, 1886, with the Pulkowa thirty-inch refractor, then newly erected, and later with smaller instruments.[7]

Besides the Maia vortex, the Paris photographs depicted a series of nebulous bars on either side of Merope, and a curious streak extending like a finger-post from Electra towards Alcyone. But all these were mere samples of what lay behind. Impressions of the Pleiades secured by Dr. Roberts with his twenty-inch reflector in October and December, 1886, showed the whole western side of the group to be involved in

[1] *Les Mondes*, t. iii. p. 529.
[2] *Harvard Annals*, vol. xiii. p. 74.
[3] *Astr. Nach.* No. 2045.
[4] *Monthly Notices*, vol. xli. p. 315.
[5] *Ibid.* vol. xl. p. 376.
[6] Similarly recorded a month earlier at Harvard College, it was taken for a flaw in the negative.
[7] *Astr. Nach.* Nos. 2719, 2726, 2730.

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one vast nebulous formation.[1] "Streamers and fleecy masses" of cosmical fog seem, in these astonishing pictures, almost to fill the spaces between the stars, as clouds choke a mountain valley. The chief points of its concentration are Alcyone, Merope, and Maia; but it includes as well Celæno and Taygeta, and is traceable southward from Asterope over an arc of 1° 10′. These photographs, in fine, as Mr. Wesley wrote, "not only prove beyond a doubt the existence of the much-disputed Merope nebula, but they also combine and harmonise in a very satisfactory manner the apparently irreconcilable drawings."[2]

The matter was not allowed to rest here. Early in 1888 the MM. Henry succeeded in giving to several plates exposures of four hours, with results identical in each case, and very curious. Their nature can be estimated from our frontispiece, which reproduces the final chart of the Pleiades prepared by the MM. Henry. The greater part of the constellation is shown in it as veiled in nebulous matter of most unequal density. In some places it lies in heavy folds and wreaths, in others it barely qualifies the darkness of the sky. The details of its distribution come out with remarkable clearness, and are evidently to a large extent prescribed by the relative situation of the stars. Their lines of junction are frequently marked by nebulous rays, establishing perhaps between them relations of an unknown nature; and masses of nebula, in numerous instances, seem as if *pulled out of shape* and drawn into festoons by the attractions of neighbouring stars. But the strangest exemplification of this filamentous tendency is in a fine, thread-like process, 3″ or 4″ wide, but 35′ to 40′ long, issuing in an easterly direction from the edge of the nebula about Maia, and stringing together "like beads on a rosary,"[3] seven stars met in its advance. Two similar rectilinear nebulæ run parallel to the first, and a fourth was photographed by M. Stratonoff in 1896.[4]

Whether these luminous highways are due to material condensations, or merely indicate tracks of electrical excite-

[1] *Monthly Notices*, vol. xlvii. p. 24.

[2] *Journ. Liv. Astr. Soc.* vol. v. p. 150.

[3] Mouchez, *Comptes Rendus*, t. cvi. p. 912; H. C. Wilson, *Astr. and Astrophysics*, vol. xiii. p. 192.

[4] *Astr. Nach.* No. 3366.

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ment, they are equally communicative upon one point. The connection by their means of stars into rows virtually demonstrates their real alignment, and thus considerably strengthens the presumption that the linear arrangement prevalent in clusters is no optical illusion, but depends upon intrinsic conditions, the outcome of universal laws.

The wonder of this aggregation of stars and nebulæ has been enhanced by Professor Barnard's discoveries. In 1890,[1] he detected visually a bright round object, like a comet without appendages, in such close proximity to Merope as to form with it probably a nondescript binary combination. Then, three years later,[2] two exposures with the Willard lens brought into view a set of curving streaks issuing from the cluster as a whole, and enfolding it exteriorly in far-reaching dim nebulosity. Its genetic history can hence be judged to be still at an early stage; yet the unity marking it is already singularly diversified. Many orders of stars are there gathered together into what might be called a miniature sidereal system, the largest of such "surpassing glory" as to dim by comparison the splendour of Sirius and Vega. The "act of order" in this "peopled kingdom" is not easy to divine; we can only see that the mutual relations of its denizens must be highly intricate. Within the wide framework of the association room is found for subordinate groupings of various characters and degrees of closeness, from stars far apart, but drifting in company, to pairs as unmistakably united by contiguity as two nuts within the same shell. Thus, the polity governing the entire system of the Pleiades would seem to be of the federative kind. Nor can we be yet sure that its bonds, while evidently so loose as to give unshackled play to local liberties, are nevertheless sufficiently strong to restrain the slow workings of disruptive tendencies.

[1] *Astr. Nach.* No. 3018. [2] *Ibid.* No. 3253.

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CHAPTER XVIII

STAR CLUSTERS

ABOUT five hundred clusters are at present tolerably well known to astronomers, and a large number besides, their character rendered ambiguous by distance, are probably included among both "resolvable" and "unresolved" nebulæ. Such aggregations may be broadly divided into "irregular" and "globular" clusters. Although, as might have been expected, the line of demarcation between the two classes is by no means sharply drawn, each has its own marked peculiarities.

Irregular clusters are framed on no very obvious plan; they are not centrally condensed, they are of all shapes, and their leading stars rarely occupy critical positions. The stars in them are collected together, to a superficial glance, much after the fashion of a flock of birds. Alcyone, it is true, seems of primary dignity among the Pleiades, and the Pleiades may be regarded as typical of irregular clusters; yet the dominance, even here, of a central star may be more apparent than real.

The arrangement of stars in clusters is, nevertheless, far from being unmethodical, even though the method discernible in it be not of the sort that might have been anticipated. It seems inconsistent with movements in closed curves, and suggests rather the description of hyperbolic orbits. Yet its true nature must obviously be greatly obscured to our perception by the annulment, through perspective, of the third dimension of space, whereby independent groupings, projected indiscriminately side by side, are rendered barely if at all recognisable. That they should, under these

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circumstances, stand out to any extent is more surprising than that they should sometimes be inextricably entangled with sprinkled stars belonging to the fore- or background. The nebulous linking together of a septuple set in the Pleiades assures us, nevertheless, that star-alineations are not illusory.

Nearly all observers have been impressed with the streaming and reticulated character of many stellar assemblages. Thus where the feet of the Twins dip into the Milky Way, an object is encountered so "marvellously striking" with a large telescope, that "no one could see it for the first time," Mr. Lassell declared, "without an exclamation." A field 19′ in diameter "is perfectly full of brilliant stars unusually equal in magnitude and distribution over the whole area. Nothing but a sight of the object itself can convey an idea of its exquisite beauty."[1] Admiral Smyth described it as "a gorgeous field of stars from the ninth to the sixteenth magnitudes, but with the centre of the mass less rich than the rest. From the small stars being inclined to form curves of three or four, and often with a large one at the root of the curve, it somewhat reminds one of the bursting of a sky-rocket."[2] A photograph of this cluster[3] by Professor Barnard, reproduced in Plate XI., Fig. 1, leaves very little doubt of its intimate galactic affinities. The sinuous lines of stars that compose it,[4] although more closely entangled than the similar catenary arrangements on the less crowded parts of the plate, can scarcely be organically distinct from them.

Yet the radiated aspect of stellar throngs lends them a quasi-individuality. The singular looped conformation visible in the "gold-dust" cluster in Auriga (M 37) attracted the attention both of d'Arrest and Lord Rosse;[5] about one hundred connected stars in Ophiuchus (N.G.C. 6494) "run in lines and arches";[6] a superb assemblage in Cassiopeia (N.G.C. 7789) was described by Lord Rosse as formed of jagged branches with

[1] *Monthly Notices*, vol. xiv. p. 76.

[2] *Cycle*, p. 168 (Chambers's ed.).

[3] M 35=N.G.C. 2168. Nebulæ and clusters throughout this volume are distinguished by Messier's well-known numbers, when among the 103 enumerated by him, otherwise by Dreyer's in the *New General Catalogue*.

[4] Secchi, *Atti dell' Accad. Pont.* t. vii. p. 72.

[5] *Trans. R. Irish Acad.* vol. ii. p. 51.

[6] *Phil. Trans.* vol. cxxiii. p. 460.

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1.

2.

Irregular Star Clusters. Photographed by E. E. Barnard.
1. Messier 35 in Gemini. 2. Double Cluster in Perseus.

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dark holes between, and by Dr. Roberts, from his photographs, as exhibiting curved and wreathed patterns in stars.[1] The constituents of a large group near the Poop of Argo (N.G.C. 2567) struck the elder Herschel by their arrangement "chiefly in rows," illustrative, to his mind, of the mechanical complexities of such systems. Each row, he observed, while possessing its own centre of attraction, will at the same time attract all the others; nay, "there must be somewhere in all the rows together the seat of a preponderating clustering power which will act upon all the stars in the neighbourhood."[2] Speculations, indeed, upon the dynamical relations of "stars in rows" are still premature, nor are they likely, for some time to come, to be accounted as "of the order of the day." But the continual recurrence in the heavens of this mode of stellar aggregation cannot fail to suggest the development of plans of systemic dissolution and recomposition on a grand scale, and involving the play of, by us, unimaginable forces.

The more attentively clusters are studied, the more intricate their construction appears. That which challenged Herschel's notice is not singular in intimating a league of several co-ordinate groups. There is rarely evidence in the conformation of irregular clusters of their being governed from a single focus of attraction; there are frequent indications of the simultaneous ascendancy of several. A cluster in Sagittarius (N.G.C. 6451) is distinctly bifid. It was remarked by Sir John Herschel at Feldhausen as "divided by a broad, vacant, straight band";[3] and his figure shows the separation as absolutely complete, the sections,

Like cliffs which had been rent asunder,

facing each other with a chasm between.

A beautiful cluster in Sobieski's shield (M 11), first noted by Kirch in 1681, seems to be extensively dislocated. Sir John Herschel succeeded, by the use of high powers, in breaking it up "into five or six distinct groups with rifts or cracks between them."[4] Father Secchi perceived in it a three-lobed

[1] *Celestial Photographs*, vol. i. p. 129.
[2] *Phil. Trans.* vol. civ. p. 269.
[3] *Cape Observations*, p. 116.
[4] *Phil. Trans.* vol. cxxiii. p. 462.

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central vacuity;[1] and M. Fenet, who in 1895 mapped from Dr. Roberts's photographs 395 of its components,[2] remarked their most likely progressive separation into seven or eight distinct allotments.

Plate XVI. shows M 11 in its Milky Way location as photographed by Professor Barnard with the Willard lens. In his opinion it is "hardly questionable" that the cluster (here necessarily contracted into a simple clump) really acts as nucleus to the vast star-clouds[3] attached to it like voluminous wings. But how strangely related such a nucleus must be to such a formation!

This "glorious object" (as Sir John Herschel called it) can just be made out with the naked eye on a perfectly clear night. Halley mentioned it in 1716 as "of itself but a small obscure spot, but with a star that shines through it which makes it the more luminous."[4] Some years later, Derham found it to be "not a nebulose, but a cluster of stars, somewhat like that which is in the Milky Way."[5] A catalogue of two hundred of the components, prepared in 1870 by M. Helmert, of the Hamburg Observatory,[6] provides material for the future investigation of relative changes.

The presence in a cluster in Monoceros (N.G.C. 2269) of "a double seat of preponderating attractions," was observed by Sir William Herschel;[7] and a throng of some two hundred stars in Cancer (M 67), discernible with an opera-glass, falls no less obviously into two divisions.[8] In a collection seen at Parsonstown to be riddled with absolutely dark "lanes and openings"[9] (N.G.C. 2548), the principle of local self-government has evidently been already carried a long way. A "reticulated mass of small stars" in Cygnus (N.G.C. 6819) was there described as "a most gorgeous cluster, *full of holes*"; and the drawing published by Lord Rosse depicts a winding

[1] *Atti dell' Accad. Pont.* t. vii. p. 75.
[2] *Bull. Société Astr. de France*, 1895, p. 85.
[3] *Astroph. Journ.* vol. i. p. 11.
[4] *Phil. Trans.* vol. xxix. p. 392.
[5] *Ibid.* vol. xxxviii. p. 72.
[6] *Publicationen der Hamburger Sternwarte*, No. 1, 1874.
[7] *Phil. Trans.* vol. civ. p. 268.
[8] Smyth, *Cycle*, p. 241; L. Fenet, *L'Astronomie*, t. vi. p. 145.
[9] *Trans. R. Dublin Soc.* vol. ii. p. 66.

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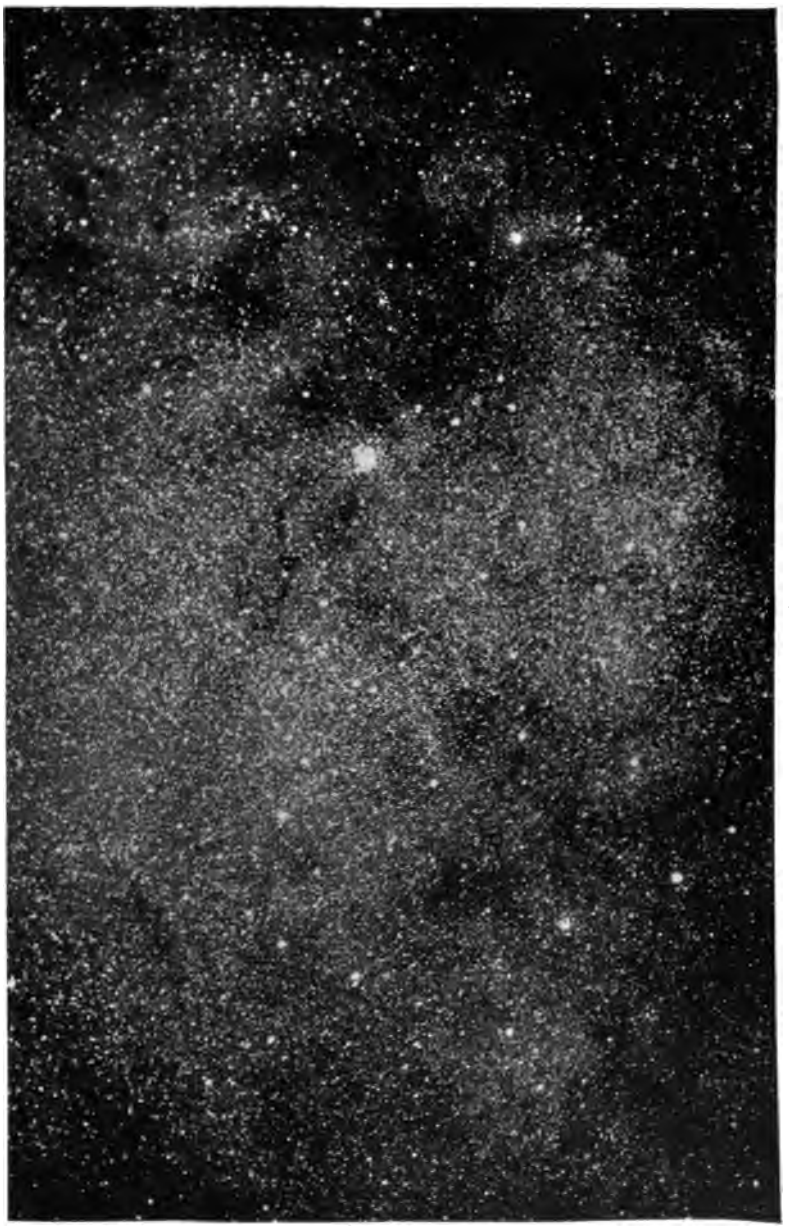
PLATE XVI.

North.

East.



West.

South.

Photograph of Messier 11 and adjacent Galactic Cloud-forms. (Barnard.)

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ribbon of stars inclosing three blank circular spaces of symmetrically varying diameters.

Among the "curiosities" of the heavens are to be reckoned clusters within clusters. Thus, a large loose collection in Gemini (N.G.C. 2331) involves a neat group of "six or seven stars close together, and well isolated from the rest."[1] A parallel instance is met with in N.G.C. 2194, situated where the Milky Way passes between Gemini and Orion; and within the bright cluster M 67 in Cancer, Dr. Roberts was struck with a knot of five stars of tenth to twelfth magnitudes, "their photo-images touching. If they should be proved," he added, "to be physically connected, the revelation would be astounding."[2]

Star-groupings of singularly definite forms frequently occur. A triangular swarm (N.G.C. 7826) presents itself in Cetus; a rectangular area in Vulpecula (N.G.C. 6802) is densely strewn with fine star-dust. Clusters shaped like half-open fans are tolerably numerous. One in Gemini, if removed to a sufficient distance, would appear, according to Sir John Herschel, "as a fan-shaped nebula with a bright point like a star at the vertex." Another specimen of an "acutangular" cluster 2′ in length (N.G.C. 7510), is bounded by "two principal lines of stars drawing to one."[3]

In Cygnus is an oval annulus, 4′ across (N.G.C. 7128), of stars centrally surrounding a ruddy one of the ninth magnitude. A similar elliptical group, with a double substituted for the red star, is centrally placed in one of the two great adjacent clusters in Perseus (N.G.C. 869).[4] This superb object, like the scarcely inferior assemblage (N.G.C. 884) it immediately precedes, was regarded by Herschel as merely a protuberance of the Milky Way, and his intuition was probably correct. The two together form a telescopic pageant such as, in the wildest flight of imagination, Hipparchus could little have dreamed would one day be unrolled before the eyes of men out of the "cloudy spot" in the sword-handle of Perseus which he (it is said) was the first to

[1] *Trans. R. Dublin Soc.* p. 56.
[2] *Celestial Photographs*, vol. i. p. 69.
[3] *Phil. Trans.* vol. cxxiii. pp. 476, 503.
[4] J. Herschel, *Phil. Trans.* vol. cxxiii. p. 373.

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detect. Their physical connection has been denied,[1] and remains unproven; yet it is strongly asserted to the eye. The second grouping (known as "χ Persei") was micrometrically investigated by Vogel in 1867-70, photographically by O. Lohse in 1884,[2] with the result, from the comparison of 172 stars, of demonstrating their fixity during an interval certainly too short for the development into visibility of such tardy movements as were alone likely to be in progress. A rapid spectroscopic survey executed by Vogel, March 30, 1876,[3] disclosed no peculiarity in the light of the components; but Mr. Espin has since recognised among them nine red stars with faintly fluted spectra. The brilliancy of this splendid throng suggests that it may be less exorbitantly distant from the earth than most other objects of its class. A fine photograph, in which "festoon-like groupings" are conspicuous, was taken of it by Mr. Roberts at Maghull, January 13, 1890.[4] That by Professor Barnard reproduced in Plate XI., Fig. 2, shows at a glance, owing to its smaller scale, the essential duplicity of the "Sword-handle" cluster.

The famous tinted cluster about κ Crucis can only be seen from southern latitudes. And it must be confessed that, with moderate telescopic apertures, it fails to realise the effect of colour implied by Sir John Herschel's comparison of it to a "gorgeous piece of fancy jewellery." A few reddish stars catch the eye at once; but the blues, greens, and yellows belonging to their companions are pale tints, more than half drowned in white light. Some of these stars are suspected of considerable mobility. During his visit to the Cape, Herschel determined the places of 110, all included in an area of about $\frac{1}{15}$ of a square degree,[5] and the process was repeated and extended to 130 components by Mr. H. C. Russell of Sydney in 1872.[6] The upshot was to bring out discrepancies which, if due to real movements, would be of extreme interest. But, under the circumstances, they only raise a distant suspicion of change, since Herschel's measurements were necessarily too hasty to be minutely reliable.

[1] Smyth, *Cycle*, p. 60. [2] *Astr. Nach.* No. 2650.
[3] *Der Sternhaufen χ Persei*, p. 31.
[4] *Monthly Notices*, vol. l. p. 315.
[5] *Cape Observations*, p. 17. [6] *Monthly Notices*, vol. xxxiii. p. 66.

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In the constellation Cancer may be seen, any fine night in winter, a blot of dim light placed midway between two fourth-magnitude stars. The stars were called by the ancients the Asses, *Aselli*, the interposed cloudlet representing to their fancy a "Manger," *Præsepe*. Since its disappearance was reckoned a sure presage of rain,[1] a good deal of popular attention was paid to it, and its stellar constitution was one of the earliest telescopic discoveries; but only preliminary steps have been taken towards its exact investigation. Of its components, thirty are measurable on Rutherfurd's photographs, and 363 were mapped over an area of three square degrees by C. Wolf some sixteen years later, eighty-two among them being carefully determined as points of reference for their fellows.[2] Asaph Hall's catalogue for 1870 of 151 of these stars has already been turned to account by Schur of Göttingen for testing the relative fixity of 45 among their number,[3] previously (in 1858) measured by Winnecke with the Bonn heliometer;[4] but no assured results as regards either their concerted, or their individual movements, have yet been elicited. Most of the stars in Præsepe yield spectra of the solar type.[5]

The particles of a drop of water are not in more obvious mutual dependence than the constituent stars of globular clusters; "the most magnificent objects," in the elder Herschel's opinion, "that can be seen in the heavens." Were there only one such collection, the probability of its separate organisation might be reckoned "infinitely infinite," and one hundred and eleven of them were enumerated by Sir John Herschel in 1864. It does not, however, follow that the systems thus constituted are of a permanent or stable character; their configuration, in fact, points to an opposite conclusion. There may, of course, be an indefinite number of arrangements by which the dynamical equilibrium of a "ball of stars" could be secured; there is only one which the present resources of analysis enable us distinctly to conceive.

[1] Aratus, *Diosemeia*, vv. 160-180, 265; Theophrastus, *De Signis Pluviarum*, ed. Heinsius, p. 419.

[2] *Comptes Rendus*, t. xcv. p. 833.

[3] *Astr. Mitth. der Göttingenschen Sternwarte*, 1895.

[4] *Ibid.* Th. ii.; *Nature*, vol. lii. p. 515.

[5] Pickering, *Harvard Annals*, vol. xxvi. pt. ii. p. 264.

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This was adverted to, many years since, by Sir John Herschel.[1] Equal revolving masses, uniformly distributed throughout a spherical space, would be acted upon by a force varying *directly* as the distance from the centre. The reason of this is easily seen; for the further out a component of such a system is located, the more matter there will be inside, and the less outside its orbit. The strength of the central pull thus reaches a maximum at the surface of the sphere, the velocity by which it is balanced growing in the same proportion. Ellipses described under these conditions would all, accordingly, have an identical period; whatever their eccentricities, in whatever planes they lay, in whatever direction they were traversed, each would remain invariable; and the harmony of a system in which no perturbations could possibly arise, would remain unbroken for ever, provided only that the size of the circulating bodies, and the range of their immediate and intense attractions, were insignificant compared with the spatial intervals separating them.

But this state of nice adjustment is a mere theoretical possibility. There is no likelihood that it has anywhere an actual existence; and the stipulations, upon compliance with which its realisation strictly depends, are certainly disregarded in all the stellar groups with which we have any close acquaintance. The components of these are neither equal, nor equably distributed. Central compression, over and above the merely apparent effect of the gradually increasing depth of the star-strata presented to the eye, is markedly effective in globular clusters. Professor Pickering, from careful photographic counts of the three typical specimens ω Centauri, 47 Toucani, and M 13 (in Hercules) deduced the rule that the number of stars per square minute of arc increases in arithmetical progression with approach to the middle point.[2] Real crowding thus intensifies the "blaze," where the stars run together, even with powerful telescopes, into an indiscriminate silvery effulgence.

Sir John Herschel acknowledged his embarrassment in even trying to imagine the "conditions of conservation of such a system as that of ω Centauri or 47 Toucani without admitting

[1] *Outlines of Astronomy*, 9th ed. p. 636.
[2] *Harvard Annals*, vol. xxvi. pt. ii. p. 218.

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repulsive forces on the one hand, or an interposed medium on the other, to keep the stars asunder."[1] Thus compacted into a whole, they might, he thought, instead of revolving individually, be supposed to rotate in their corporate capacity as a single body. But the establishment in such aggregations of a "statical equilibrium" by means of an "interposed medium," is assuredly chimerical. The hypothesis of their rotation in one piece is countenanced by no circumstance connected with them. It is decisively negatived by their irregularities of figure. The sharp contours of bodies whirling on an axis are nowhere to be found among these objects. Their streaming edges betray a totally different mode of organisation.

Globular clusters commonly present a radiated appearance in their exterior parts. They seem to throw abroad feelers into space. The great cluster in Hercules is not singular in the display of "hairy-looking, curvilinear" branches. That in Canes Venatici (M 3) has "rays running out on every side" from a central mass, in which "several small dark holes were disclosed by Lord Rosse's powerful reflectors;[2] showing pretty plainly that the spiral tendency, visible in the outer regions, penetrates in reality to the very heart of the system. From a well-known cluster in Aquarius (M 2), "streams of stars branch out, taking the direction of tangents."[3] That in Ophiuchus (M 12) is provided with long straggling tentacles, of a "slightly spiral arrangement," according to the same authority. And a remarkable assemblage in Coma Berenices (M 53) was described by Herschel and Baily as "a fine compressed cluster with curved appendages like the short claws of a crab running out from the main body."[4] The peculiarity in question is the more significant that it is shared by many undoubted nebulæ.

We find it difficult to conceive the existence of "streams of stars" that are not *flowing*; and accordingly the persistent radial alignment of the components of clusters inevitably suggests the advance of change, whether in the direction of

[1] *Cape Observations*, p. 139.
[2] *Trans. R. Dub. Soc.* vol. ii. p. 132.
[3] *Ibid.* p. 162.
[4] *Phil. Trans.* vol. cxxiii. p. 458.

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concentration or of diffusion. Either the tide of movement is setting inward, and the "clustering power" (to use a favourite phrase of Sir William Herschel's) is still exerting itself to collect stars from surrounding space; or else a centrifugal impulse predominates, by which full-grown orbs are driven from the nursery of suns in which they were reared, to seek their separate fortunes, and enter on an independent career elsewhere. But the question as to whether separatist or aggregationist tendencies prevail in globular clusters is, for the present, beyond the range of profitable discussion. All that can be said is that, after the lapse of some centuries, photographic measurements may help towards deciding it.

An object visually resembling a blurred star below the fourth magnitude, was named by Bayer ω Centauri. It never rises in these latitudes, but Herschel's great reflector revealed it to him at the Cape as a "noble globular cluster, beyond all comparison the richest and largest object of the kind in the heavens."[1] The stars contained in it are, strictly speaking, innumerable. About 6400 have been enumerated from the best photographic plates;[2] but a residuum of mottled haze indicates the reckoning to be far from exhaustive. Those individualised are nearly all brighter than the fourteenth, fainter than 12·5 magnitude; and no less than 125 among them have been found by Professor Bailey to flash and fade in periods ranging from $4{\cdot}75^{d}$ to $6^{h}\ 11^{m}$. The diameter of this stellar swarm is put at $40'$, but some 1600 of its apparent constituents are held to belong to the general population of the sky.

The loveliness of the cluster 47 Toucani near the Lesser Magellanic Cloud was, to Herschel's view, set off by a diversity of colour between an interior mass of rose-tinted stars and marginal strata of purely white ones.[3] But the effect was doubtless subjective; it met with no later recognition; and to the present writer, in 1888, the sheeny radiance of this exquisite object appeared of uniform quality from centre to circumference. A photograph of it, secured November 17,

[1] *Cape Observations*, p. 21.

[2] *Astr. and Astrophysics*, vol. xii. p. 691; *Harvard Annals*, vol. xxxviii. p. 5 (Bailey).

[3] *Cape Observations*, p. 18.

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1902, at the Royal Observatory, Cape of Good Hope, is, through the kindness of Sir David Gill, reproduced in Plate XII., Fig. 2. Probably no other cluster exhibits an equal degree of compression. Within a sphere of 11′ radius are included nigh upon 10,000 stars, of which 5019 have been actually counted.[1] The blankness of the surrounding sky renders 47 Toucani all the more obvious to unaided sight; it was, indeed, for several nights after his arrival in Peru, mistaken by Humboldt for a comet.[2] Only eight variables have been detected in it—a scanty gleaning compared with the rich harvests gathered in ω Centauri, and in the starry spheres M 5 and M 3, situated in Serpens and Canes Venatici respectively. The last-named collection shelters at least 132 flickering lights, being one in seven of its individualised components. Those of several other clusters, nevertheless, shine with remarkable stability; and these contrasts seem unrelated to diversities of structure or quality in the groups manifesting them.

The gradations of lustre are, in many of these aggregations, distributed on a clearly traceable plan. As a general, if not an invariable rule, the smaller stars are gathered together in the middle, while the bright ones interpenetrate them in rows and branches. Thus, of a magnificent cluster in Sagittarius (M 22), known since 1665, the central portion accumulates the light of multitudes of excessively minute, and is freely sprinkled over with larger stars. Sir John Herschel remarked of a cluster in the southern constellation of the Altar (N.G.C. 6752): "The stars are of two magnitudes; the larger run out in lines like crooked radii, the smaller are massed together in and around the middle."[3] A similar arrangement was noted by Webb[4] in the Canes Venatici and Coma Berenices clusters (M 3, M 53), as well as in the imposing collection in Serpens above referred to, the more condensed part of which (compared by Sir John Herschel to a snowball) seems as if "projected on a loose, irregular ground of stars."[5]

[1] Bailey, *Harvard Annals*, vol. xxxviii. p. 249.
[2] *Cosmos* (Otté's trans.), vol. iii. p. 192.
[3] *Cape Observations*, p. 119.
[4] *Student*, vol. i. p. 460.
[5] *Phil. Trans.* vol. cxxiii. p. 359.

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Irregularities of distribution in clusters assume at times a highly enigmatical form. At Parsonstown, in 1850,[1] three "dark lanes," meeting at a point considerably removed from the centre, were perceived to interrupt the brilliancy of the globe of stars in Hercules (M 13). They were afterwards recognised by Buffham and Webb, and recorded themselves with emphasis in a photograph taken by Dr. Roberts in 1887. Globular clusters in Ophiuchus (M 12), in Pegasus (M 15),[2] and in Canes Venatici (M 3), appear to be similarly tunnelled. Preconceived ideas as to the mechanism of celestial systems are utterly confounded by phenomena not easily reconcilable with the prosecution of any orderly scheme of circulatory movement. The seeming rifts, however, are not absolutely vacant. A study of the cluster in Hercules (M 13) by Mr. H. K. Palmer,[3] from plates exposed with the Crossley reflector, brought out the singular fact that its components fall generally into two orders, the distribution of which is radically different. The faint stars, or those below 13·5 magnitude, are scattered with fair uniformity throughout a spherical space; those brighter obey a streaming tendency, and the gaps between their ramifications show as dark lanes. The same explanation is doubtless valid in all similar cases.

Differences of distance are alone adequate to account for the variety of *texture* observable in globular clusters. That in Aquarius, for instance, likened by Sir John Herschel to "a heap of golden sand," might very well be the somewhat coarse-grained Hercules group withdrawn as far again into space. At a still further stage of remoteness, the appearance would presumably be reached of a stellar throng in the Dolphin (N.G.C. 6934), which, with low powers, might pass for a planetary nebula, but under stronger optical compulsion assumes the granulated aspect of a true cluster. And many more, their genuine nature rendered impenetrable by excessive distance, are possibly reduced to the featureless semblance of "irresolvable" nebulæ.

But there are real, as well as apparent diversities in these objects. Although smaller and more compact clusters must,

[1] *Phil. Trans.* vol. cli. p. 732.
[2] Webb, *Cel. Objects*, p. 372.
[3] *Astroph. Journ.* vol. x. p. 246.

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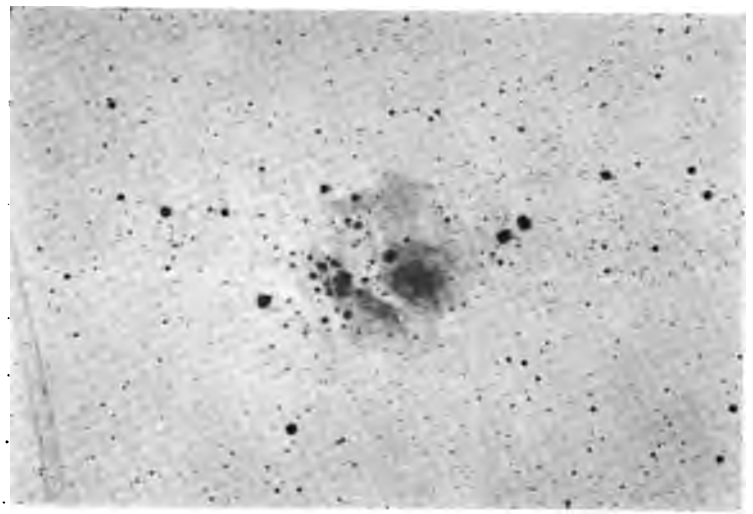
1.



2.

Photographs of Southern Sidereal Objects.

Fig. 1. Photograph of Messier 8, taken with the Bruce Telescope by S. I. Bailey.
Fig. 2. Photograph of 47 Toucanæ, taken at the Royal Observatory, Cape of Good Hope.

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on the whole, be more remote than large, loosely-formed ones, yet "this argument," Sir William Herschel remarked, "does not extend so far as to exclude a real difference which there may be in different clusters, not only in the size, but also in the number and arrangement of the stars." There may be globular clusters with components of the actual magnitude of Sirius; others, optically indistinguishable from them, may be aggregated out of self-luminous bodies no larger than Mars, or even than Ceres or Pallas. Our total inability to locate them in space leaves us without the means of judging. Nor are we likely to be better provided in this respect for an indefinite time to come. All that can be done is to make a supposition, and trace the consequences. Let our example be the great cluster in Hercules.

"This is but a little patch," Halley wrote in 1716, but it shows itself to the naked eye when the sky is serene, and the moon absent.[1] Messier termed it "nébuleuse sans étoiles";[2] yet a "twinkling" indicative of its stellar character may be caught with a telescope four inches in aperture; and a powerful instrument resolves it to the core. Within the precincts of Halley's "little patch," Sir William estimated fourteen thousand stars to be "cribb'd, cabined, and confined!"

The apparent diameter of this object, including most of the "scattered stars in streaky masses and lines,"[3] which form a sort of "glory" round it, is 18′; that of its truly spherical portion may be put at 14′. Now a globe subtending an angle of 14′ must have a real diameter $\frac{1}{245}$ of its distance from the eye, which if we assume to be such as would correspond to a parallax of $\frac{1}{20}$ of a second, we find that the cluster, outliers apart, measures 1,600,000 millions of miles across. Light, in other words, occupies about ninety-seven days in traversing it, while it needs sixty-five years to journey thence hither. Its components may be regarded, on an average, as of 13·5 magnitude; and Mr. Palmer reckoned at 5482 the number distinctly printed on the Crossley plates.

If, then, 5500 stars be supposed uniformly distributed through a sphere 1,600,000 million miles in diameter, an

[1] *Phil. Trans.* vol. xxix. p. 392.
[2] *Conn. des Temps*, 1784, p. 233.
[3] *Phil. Trans.* vol. cxxiii. p. 458.

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interval, roughly, of 61,000 million, or more than twenty-five times the distance of Neptune from the sun, separates each from its nearest neighbour.[1] Upon a spectator in an intermediate situation, six stars (besides crowds of graduated inferiority) would shine with about sixteen times the lustre that Sirius displays to us. Yet since 625 million stars of this brilliancy would be needed to supply the light we receive from the sun, the general illumination of the cluster cannot greatly exceed the qualified darkness of a star-lit night.

At its surmised distance, our sun would appear as a star of 6·3 magnitude; it would shine, that is to say, about 760 times as brightly as an average one of the grouped objects. Each of these, accordingly, emits $\frac{1}{760}$ of the solar light; and if of the same luminosity relative to mass as the sun, it exercises just $\frac{1}{20,000}$ of the solar attractive power. The mass of the entire system of 5500 such bodies is accordingly less than one-third that of our sun. This may be regarded as a minimum estimate. The probabilities are in favour of the cluster being vastly more remote than we have here assumed it to be; hence composed of larger or brighter and presumably more massive individual bodies than results from our calculation.

No insight has yet been obtained into the mode of formation of globular clusters. Their antecedent state remains wholly obscure. True nebulosity appears to be absent from them. All those examined by Professor Barnard with the great Yerkes refractor proved throughout unmistakably stellar. The nebular relations of less condensed groups are, on the other hand, frequently very close; and their photographic study has amply justified the conjecture that the two classes of object form an unbroken series—that clusters exist in every stage of development from nebulæ, and that the advancing condensation of many nebulæ will eventually transform them into veritable clusters. Suggestions to this effect derived from analogies of form,[2] are corroborated by numerous observations of the actual coexistence with grouped stars of nebulous masses. The Pleiades is the palmary but not a solitary

[1] See Mr. J. E. Gore's analogous calculations in *Journ. Liv. Astr. Soc.* vol. v. p. 169; *Studies in Astronomy*, p. 80 (1904).

[2] Lockyer, *Proc. R. Society*, vol. xliv. p. 29.

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instance of a hybrid system. A bright cluster of the same general character in Sagittarius (N.G.C. 6530) is obviously connected with a great nebula (M 8), in the meshes of which it seems as if entangled. Yet the two formations are not strictly concentric. The cluster follows, while it overlaps the nebula. Nor do the cosmic floccules adhere so closely to individual stars as in the Pleiades. Plate XII., Fig. 1, shows a photograph of the combination taken at Arequipa with the Bruce telescope, June 11, 1896;[1] and a group of nebulous stars in the immediate neighbourhood was detected by Professor Barnard on a plate exposed during four and a quarter hours, June 25, 1892.

A suggestive photograph of a "cloudy vortex"[2] in Monoceros (N.G.C. 2237-39) was taken by Dr. Roberts, March 5, 1899. Within a series of annular undulations (so to call them) of nebulous matter covering a sky-space one degree across, a straggling cluster is centrally situated. The associated effect strongly recalls that of Nova Persei with its web of glimmering whorls, and intimates possibly an analogous genetic tie.

The spectra of clusters while, in the main, continuous, are probably not devoid of individual peculiarities. Sir William Huggins was struck, in 1866, with the absence of red rays from the analysed light of the great cluster in Hercules, and perceived in it irregularities due either to bright or dusky bands.[3] They were construed in the latter sense by Vogel in 1871,[4] since when the inquiry has been unaccountably neglected. With the powerful instruments of modern construction, it might, nevertheless, be profitably extended by spectrographic means to many globular assemblages; and the results to be expected from it are a *sine quâ non* for advancing much further our imperfect acquaintance with them.

[1] *Harvard Circular*, No. 15.

[2] Mrs. Roberts, *Journ. Brit. Astr. Ass.* vol. xii. p. 111; see also Barnard, *Astr. Nach.* No. 2918, *Astr. and Astrophysics*, vol. xiii. pp. 178, 642.

[3] *Phil. Trans.* vol. clvi. p. 389.

[4] *Astr. Nach.* No. 1864.

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CHAPTER XIX

THE FORMS OF NEBULÆ

THE fantastic variety of nebular forms was long a subject of wonder; and although wonder, in the Baconian phrase, be "broken knowledge," the fragments were not readily pieced together. Inchoate worlds, disclosed with astonishing profusion by great telescopes, seemed like mere "sports of nature" in the sidereal spaces. Nebulæ were to be found in the semblance of rings, fans, brushes, spindles; they abounded in planetary, cometary, elliptical, branching varieties; nebulous shields, embossed with stars, or tasselled like the ægis of Athene, displayed themselves, as well as nebulous discs, rays, filaments, triangles, parallelograms, twin and triple spheres. One nebula, thought to resemble the face of an owl, was named accordingly; another suggested a crab; a third a swan; a fourth (the great Orion formation) became known as the Fish Mouth nebula, from its supposed likeness to the gaping jaws of a marine monster. Fancy ranged at large through this wide realm, attempting to familiarise itself with the strange objects contained in it by finding for them terrestrial similitudes.

Within the last few years, however,—indeed, it may be said, since the completion of the Rosse reflector in 1845,—nebular inquiries have entered upon a new phase. A "glimmering of reason" has begun to hover over what long appeared a scene of hopeless bewilderment. With improved telescopic means—above all, with the aid of photography—*structure* has become increasingly manifest among all classes of nebulæ. Structure, not of a finished kind, but indicating with great

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probability the advance of formative processes on an enormous scale, both as regards space and time. Masses that seemed all but amorphous when imperfectly seen, show to a keener scrutiny nodes and nuclei of condensation; curving lines of light, telling of the presence of movement and force, furrow them; they are perceived to be rifted as if by a colossal thunderbolt, or riddled as if by a portentous cannonade. Simple milky effusions prove to be far less common than had been supposed, and excessive complexity of constitution is already a recognisable characteristic of most nebulæ.

It is one which adds greatly to the interest of their study. For as the curious details of their organisation are laid bare by the intricate inequalities of their light, the prospect grows hopeful of gaining some insight into the nature of the systems formed by, or in preparation from them. Optical discoveries, while gradually acquiring physical significance, are helping to lay the foundation of a "nebular theory" emanating from augmented knowledge, and the discreetly adventurous thoughts which it may be supposed to countenance.

Meanwhile, some mode of nebular classification has to be adopted for the guidance of our ideas; and since their rapid modification through fresh detections allows no arrangement to be at present more than provisional, it will be best to depart as little as possible from that already in use. We may, then, for descriptive purposes, divide nebulæ into the following eight classes, which, nevertheless, frequently overlap so widely as to be barely distinguishable:—(1) Nebulous stars; (2) Planetary nebulæ; (3) Annular nebulæ; (4) Cometary nebulæ; (5) Spiral nebulæ; (6) Double nebulæ; (7) Elliptical nebulæ; (8) Irregular nebulæ.

In the course of one of his "reviews of the heavens," Sir William Herschel discovered a star in Taurus "perfectly in the centre" of a "faintly luminous atmosphere" about 3′ in diameter.[1] The consideration of this object (N.G.C. 1514) and of some others like it, led him in 1791 to the memorable conclusion that there exists in space "a shining fluid of a nature totally unknown to us." Nothing, indeed, could be clearer than that "the nebulosity about the star was not of a starry nature," and there is just as little doubt that it is

[1] *Phil. Trans.* vol. lxxxi. pp. 71, 82.

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no atmosphere in the ordinary sense of the word. This is demonstrated by its extent alone. For the "glow" round Herschel's pattern nebulous star fills a sphere by a moderate estimate thirty times as wide, or 27,000 times as capacious, as that enclosed by the orbit of Neptune; and the Rosse telescope disclosed irregularities of illumination within it,[1] entirely inconsistent with the prevalence of gaseous equilibrium. Thirteen nebulous stars were enumerated by Herschel, and many have since been added to them. A fine specimen in Eridanus was picked up by Swift in 1859;[2] a small star in Ursa Major came out strongly "burred" on one of Dr. Roberts's plates in 1889;[3] and Professor Barnard's photographic explorations have yielded numerous examples of a similar nature sometimes associated into multiple groups. Among Sir John Herschel's southern discoveries was a close, sharply-defined double star surrounded by a bright luminous "atmosphere" 2′ in extent[4] (N.G.C. 5367); one of Burnham's close pairs is in slow revolution, as already mentioned, at the heart of the nebula N.G.C. 2182; while nebulous spectroscopic binaries, despite their apparently incongruous circumstances, are beginning to take rank among the ordinary products of the sidereal world.

A "nebulous star" proper forms the centre of an ill-defined aureola; but nebulous adjuncts to stars exist in every variety of branches and chevelures, wisps and whorls. Indeed the sequence is so continuous between bright stars with filmy appendages, and pronounced nebulæ involving minute stars, that it is often difficult to say whether the stellar or the nebular character predominates. Thus, "planetary" nebulæ have, with rare exceptions, stellar nuclei; they can be discriminated, however, from nebulous stars, first, by their predominantly gaseous spectra, next, by the definite termination of their discs.

It is then no wonder if, among Herschel's nebulous stars, one was found not strictly entitled to bear that name. This nondescript object (N.G.C. 2392) is situated in Gemini, and

[1] *Trans. R. Dub. Soc.* vol. ii. p. 40.
[2] *Sidereal Messenger*, vol. iv. p. 39.
[3] *Monthly Notices*, vol. xlix. p. 363.
[4] *Cape Observations*, pp. 23, 107.

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that it struck him as something unusual may be inferred from his designating it "one of the most remarkable phenonema I have ever seen."[1] With the Parsonstown reflector it presented a most "astonishing" appearance. Herschel's "equally diffused nebulosity" was replaced by several bright and dark rings, various in breadth, and perhaps spiral in their arrangement.[2] The diameter of the combination is about 45″, and doubts about its nature were set at rest by the dictum of the spectroscope. D'Arrest[3] found its light to be concentrated in the green ray of nebulium (wave-length 5007)—the central star or nucleus asserting its superior condensation by the display of a faint continuous radiance. It is then essentially a nebula, and generally passes for one of the annular, or perforated kind. A truly nebulous star of a reddish colour, makes with it (not, we may surmise, fortuitously), an open pair at 105″.[4]

A nebula in Aquila (N.G.C. 6781) presents analogies to Herschel's burred star in Gemini. J. Herschel considered it to be of planetary nature; but the Rosse reflector showed a sudden diminution of brightness towards the middle,[5] and Barnard unhesitatingly pronounces for its annularity.[6]

Planetary nebulæ were first distinctively adverted to by Sir William Herschel. Their classification caused him a good deal of perplexity. "We can hardly suppose them," he remarked at starting, "to be nebulæ; their light is so uniform as well as vivid, the diameters so small and well-defined, as to make it almost improbable they should belong to that species of bodies." After he had weighed and found wanting the hypotheses of their being actual planets belonging to distant suns, or distended stars, or comets near aphelion, he, nevertheless, at last decided—rightly, as usual—in favour of their nebulous nature.[7]

[1] *Phil. Trans.* vol. lxxxi. p. 81.

[2] *Trans. R. Dub. Soc.* vol. ii. p. 59; see also H. C. Key, *Monthly Notices*, vol. xxviii. p. 154.

[3] *Astr. Nach.* No. 1885; *Abhandlungen*, Leipzig, Bd. iii. p. 321.

[4] Lassell, *Memoirs R. Astr. Soc.* vol. xxxvi. pp. 42, 61.

[5] *Trans. R. Dub. Soc.* vol. ii. p. 59; *Phil. Trans.* 1861, p. 732.

[6] *Monthly Notices*, vol. lx. p. 256.

[7] *Phil. Trans.* vol. lxxv. p. 265.

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Fifty of them were known when Pickering began "sweeping" in 1881, for "stars with remarkable spectra";[1] and within a few years, upwards of twenty more were identified, through the quality of their light alone, by him and Dr. Copeland. These are, however, devoid of the conspicuous disc which was the original badge of their class; they are either very small, or very remote planetaries; and are often distinguished as "stellar nebulæ."

A true "planetary" aspect has not, indeed, in any case survived the scrutiny of modern observers. What had seemed equably illuminated discs are broken up by the powerful telescopes now in use, into brighter and darker portions, distributed in evident relation to some unknown conflict of forces. Some of these discs include strongly-marked nuclei; others a sprinkling of minute stars; condensation towards a spherical surface gives to many the aspect of a ring-shaped enclosure; few (if any) are clean at the edges.

Not a few are seemingly multiplex. Two or three superposed discs are traceable in them, hinting at a morphological history similar to that of disturbed comets. Thus a small oval planetary (N.G.C. 6572) in Ophiuchus was resolved by Vogel with the great Vienna refractor in 1883,[2] into three strata of nebulosity disposed as in Fig. 28, representing, no doubt, successive spherical and ellipsoidal envelopes of diminishing luminous power.

Fig. 28.—Plan Sketch of a Nebula (Vogel).

An object (N.G.C. 6210) with an "intense blue centre fading off to some distance all round," and hazy at the edges,[3] was perceived by Vogel as triple. A faint oval *husk* (so to speak) seemed to enclose a vivid kernel, and that again to include a stellar nucleus. This nebula is situated in the constellation Hercules; and one of a similar character in Eridanus (N.G.C. 1535), was described at Parsonstown as presenting a granular, Nile-water blue disc 18″ across, including a stellar nucleus, and encircled with a faint atmosphere.[4] Mr. Lassell noted the combined effect as

[1] *Observatory*, vols. iv. p. 81, v. p. 294; *Monthly Notices*, vol. xlv. p. 91.
[2] *Potsdam Publicationen*, No. 14, p. 34.
[3] *Trans. R. Dub. Soc.* vol. ii. p. 150.
[4] *Ibid.* p. 41.

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"extraordinary and beautiful."[1] Such "nebulous nebulæ" (to borrow Dr. Swift's phrase)[2] are among the most enigmatical of celestial objects.

Of special interest among planetary nebulæ is one lying quite close to the pole of the ecliptic, near the star ω Draconis (N.G.C. 6543). Its longer diameter (for it is slightly elliptical) measures about 30″; it is of a blue colour, and shows a white star of eleventh magnitude giving a perfectly continuous spectrum exactly in the middle of a disc from which a purely gaseous one is derived. Sir William Huggins's first experiment in the analysis of nebular light was in fact tried upon the planetary in Draco, which has in various ways been used as a test object. Attempts to determine its parallax were vainly made by d'Arrest, Brünnow, and Bredichin.[3] For proper motion, too, it was tested by d'Arrest in 1872, with a similarly negative result. During the eighty-two years' interval since a careful observation by Lalande in 1790, the nebula had remained to all appearance completely stationary. But this fixedness was really to some extent communicative as regards its *minimum* distance from the earth. D'Arrest showed that unless this exceed a light-journey of forty-seven years, the nebula must have become sensibly displaced in the course of eighty-two years by the simple perspective effect of the sun's advance at the rate of five miles a second.[4] Now the solar velocity assuredly does not fall short of twelve miles a second, while the term of the nebula's seeming immobility has become protracted from 82 to 115 years. The estimate of its distance needs, on both these grounds, to be augmented; and we find, accordingly, that its light can only reach our eyes after an interval of nearly 160 years,[5] *if then*; for it may spend a much longer time on the road. The real size of the globe it emanates from must be vast in proportion to such

[1] *Memoirs R. Astr. Soc.* vol. xxxvi. p. 40.

[2] *Astr. Nach.* No. 3474.

[3] Brünnow obtained for H iv. 37 a nominal parallax, but Bredichin, from nearly double the number of observations, derived a *negative* one implying the nebula to be more remote than the tenth-magnitude star with which it was compared. *Astr. Nach.* No. 2916 (Oudemans); *Eng. Mec.* vol. xliii. p. 504 (H. Sadler).

[4] *Astr. Nach.* No. 1885.

[5] Corresponding to a parallax of 0″·02.

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extreme remoteness. Not less, indeed, than twenty-five diameters of the orbit of Neptune would be needed to measure it from side to side.

The question, however, might be raised as to whether the figure of the Draco planetary is even approximately globular. Helical lines of structure were discerned in it by Professors Holden and Schaeberle in 1888[1] (see Fig. 29), and the coiling shape indicated was to some extent confirmed by a photograph taken at Meudon in 1899.[2] A "large, pale planetary" in Sagitta (N.G.C. 6905), with a closely attendant star at each side,[3] was easily resolved into a spiral by

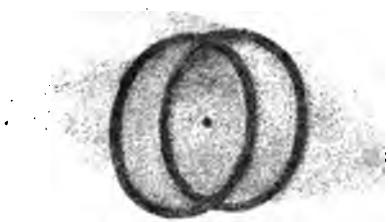

FIG. 29.—Helical Nebula in Draco (Holden).

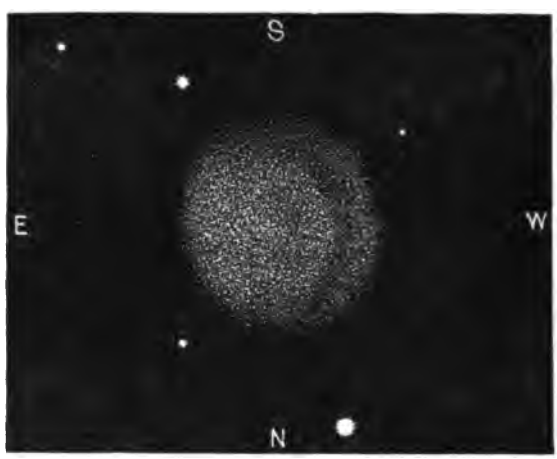

FIG. 30.—Spiral Planetary Nebula in Sagitta (*Knowledge*, vol. xxiii. p. 250).

M. Antoniadi, with the great Paris siderostat.[4] His drawing, reproduced in Fig. 30, shows the object under a form similar to that presented by the "Great Whirlpool" nebula until

[1] *Monthly Notices*, vol. xlviii. p. 388; *Publ. A. S. P.* vol. i. p. 25.
[2] Deslandres, *Bull. Astr.* Feb. 1900.
[3] Keeler, *Publ. Lick Observatory*, vol. iii. p. 213.
[4] *Knowledge*, vol. xxiii. p. 250.

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the compelling power of the Rosse reflector was brought to bear on it.

These are not isolated examples. A considerable number of planetary nebulæ, as we have already partly seen, manifest both annular and spiral tendencies. In some a marginal brightening gives, with sufficient light-concentration, the effect of a ring; in others, curvilinear effects of chiaroscuro betray incipient spirality of conformation. Since they partake of the nature of all the three species, their classification is to a great extent arbitrary. Five of Herschel's planetaries assumed, in fact, at Parsonstown a ring-shape.[1] One of these (N.G.C. 2438), remarkably situated within the cluster M 46 in Argo, was observed not alone to be pierced with a nearly central cavity, but to contain two, perhaps three stars, towards one of which the exterior nebulous ring wound spirally inward.[2] A "hole" too disclosed itself in a planetary in Andromeda (N.G.C. 7662) observed by Lassell as biannular, "a ring within a ring." To Father Secchi, it had, with high powers, the effect of a "magnificent horseshoe of scintillating points,"[3] the glitter of which was also evident to Vogel.[4] It is, nevertheless, like all the members of its class, of a purely gaseous constitution. The "biannular" planetary is either hazy or "fringed" at the edges, of a bluish colour, and measures 32″ by 28″.[5] An effusion from its south-eastern extremity was photographed by Deslandres.[6]

The blue, or greenish tinge distinguishing, to some extent, all gaseous nebulæ, is especially conspicuous in a planetary (N.G.C. 3918), discovered by Sir John Herschel in the Centaur, and described as very like Uranus, only half as large again, its "colour a beautiful rich blue, between Prussian and verditer green."[7] And a "sky-blue likeness of Saturn" replaced, in Mr. Lassell's reflector, a round, faintly lucent object (N.G.C. 7009) observed by Herschel in 1782 near the star ν Aquarii. With higher powers, the disc became a ring 26″ by 16″, hazy within and without; and the whole

[1] *Phil. Trans.* vol. cxl. p. 507. [2] *Ibid.* p. 513.
[3] *Astr. Nach.* No. 1018; *Les Étoiles*, t. ii. p. 14.
[4] *Potsdam Publicationen*, No. 14, p. 37.
[5] Lassell, *Memoirs R. Astr. Soc.* vol. xxxvi. p. 51.
[6] *Bull. Astr.* Feb. 1900.
[7] *Cape Observations*, p. 100.

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interior assumed, under Vogel's examination, a curious screw-shaped structure.[1] Professor Holden remarked an unexpected point of likeness between this nebula and the one in Andromeda (N.G.C. 7662), in the possession by both of an interior oval ring, singularly warped and twisted out of the central plane; the peculiarity associating them also with the helical planetary in Draco. The ansæ, or handle-like appendages producing in the object near ν Aquarii its resemblance to Saturn with half-opened rings, are a unique feature among nebulæ. First represented by Lord Rosse, they were resolved by Professor Holden[2] into distinct luminous masses, just traceably connected with the main body (see Fig. 31).

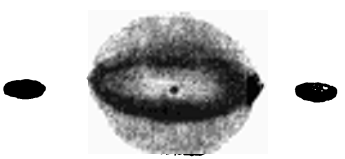

Fig. 31.—Annular Nebula in Aquarius (Holden).

The analogy with satellite-stars is tempting, but may be misleading. The frequent attendance of small stars upon nebulæ both planetary and annular long ago attracted the attention of Sir John Herschel.[3] One such group (N.G.C. 6818) struck him as exactly like a planet and pair of moons, and stars in slow transit across a nebula of which they are the dependents, may often appear projected upon it. But not the slightest evidence of movement in these ancillary stars has yet been detected.

The typical annular nebula (M 57) was detected by Darquier of Toulouse in 1779, between β and γ Lyræ. It consists of an oval bright ring, 80″ by 60″, the interior of which is filled with a dim nebulous haze like "gauze stretched over a hoop."[4] Harding, already in 1797, perceived irregularities in the illumination of the ring;[5] and vivid patches emphasise the extremities of the minor axis. Minima of light, on the contrary, terminate the major axis; the nebula, as photographed at Herény, September 1, 1886, taking somewhat the shape of a pair of parentheses set a little apart, thus ⁀, but with spiral links between.[6] With the Rosse

[1] *Potsdam Publicationen*, No. 14, p. 37.
[2] *Monthly Notices*, vol. xlviii. p. 391. [3] *Phil. Trans.* vol. cxxiii. p. 500.
[4] Sir J. Herschel's *Outlines of Astr.* p. 644, 9th ed.
[5] Holden, *Monthly Notices*, vol. xxxvi. p. 64.
[6] Von Gothard, *Astr. Nach.* No. 2749.

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reflector, filaments of nebulosity were seen streaming outward from the edges;[1] and the reality of these singular appendages was, after fifty-three years, photographically attested with the Crossley reflector.[2]

A central star, discerned in this nebula by von Hahn at Remplin, towards the close of the eighteenth century, was missed by him in 1800,[3] and has often since evaded the scrutiny of better provided observers. It appeared on the Herény and Liverpool photographs,[4] but notwithstanding its intense actinic quality, left no trace on plates exposed at Paris.

Dr. Max Wolf's recent photographs lend some countenance to the explanation of these anomalies by genuine variability.[5] This insignificant light-speck appears to be the very *punctum saliens* of the surrounding nebulous organism. Professor Schaeberle's photographs, taken in 1903 with a reflector of extraordinarily short focus, display it as the origin of a pair of oppositely issuing branches which, coiling in a clockwise direction, produce by their amalgamation the effect of a complex ring.[6] Moreover, the ring is now seen to be the nucleus of a larger formation, 15′ in diameter, which embraces in its dim folds a small nebula, also a "two-branched, left-handed spiral," discovered by Professor Barnard in 1893. These surprising results, although needing full verification, are recommended to acceptance by the unity they impart to facts previously disjointed and fragmentary.

A nebula in Cygnus (N.G.C. 6894) might be called a reduced copy of that in Lyra. It measures 47″ by 41″, the interior vacuity, which is partially filled with faint light, 20″. A conspicuous star is included within it.[7] An object of the same kind in Scorpio (N.G.C. 6337) was described by Sir John Herschel as "a beautiful delicate ring of a faint ghost-like appearance, about 40″ in diameter."[8] Two stars, or nebulous nodes, are placed in it exactly opposite to each

[1] *Phil. Trans.* vol. cxxxiv. p. 322.
[2] Keeler, *Astroph. Journ.* vol. x. p. 196.
[3] *Astr. Jahrbuch*, 1802, p. 10.
[4] Von Gothard, *Astr. Nach.* No. 2754; Spitaler, *ibid.* No. 2800.
[5] *Astr. Nach.* No. 3844.
[6] *Astr. Journ.* Nos. 539, 547.
[7] Lord Rosse, *Trans. R. Irish Acad.* vol. ii. p. 156.
[8] *Cape Observations*, p. 114.

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other, and the whole aspect of the nebula suggests extreme remoteness.[1]

Four ring-nebulæ, two in the northern, two in the southern hemisphere, were known to the Herschels; and, as we have seen, many so-called "planetaries" show annular, as annular nebulæ show spiral proclivities. Rings, in some instances, visibly curve inward towards a nucleus, giving rise to the variety which we have designated "cometary" nebulæ. Thus, a ninth-magnitude star with nebulosity attached (N.G.C. 1999) appeared with the Rosse reflector like "a comet coiled into a ring"[2] and was photographed, precisely under the same aspect, by Dr. Common in 1883.[3] The triple star, ι Orionis, less than a degree distant, is enveloped in a nebula of analogous form, which is also less definitely shown by the appendage of the star Maia in the Pleiades. Sir John Herschel's "falcated" nebulæ are of the same kind. One such in Argo, 10′ in extent (N.G.C. 3199) displayed to him a "semi-lunar shape," diffuse outside, but with a sharp inner edge.[4] Another (N.G.C. 346) occurs far to the south in Hydrus. "A complete telescopic comet, a perfect miniature of Halley's,"[5] was encountered in Eridanus (N.G.C. 1325), and star-like condensations, with brush, or fan-like appurtenances, are not unfrequently entered on his lists. A pair of small nebulæ photographed by Wolf and Barnard near the bright star γ Cassiopeiæ[6] are singularly perfect examples of rectilinear cometaries. They imitate precisely half-opened fans; the emanation from the star at the vertex has had no curvature impressed upon it; it spreads from a point without enfolding it; the rotational twist seems absent.

The discovery of spiral nebulæ was beyond question the most important result of the construction of the great Parsonstown reflector. Its significance is continually enhanced as the wide prevalence of convoluted forms among this whole class of sidereal objects is rendered more fully apparent by the increasing advance of exploration.

The Whirlpool nebula in Canes Venatici (M 51) presents,

[1] Lassell, *Memoirs R. Astr. Soc.* vol. xxxvi. p. 47.
[2] *Trans. R. Dub. Soc.* vol. ii. p. 50. [3] *Observatory*, vol. xii. p. 84.
[4] *Cape Observations*, pp. 20, 94. [5] *Ibid.* p. 61.
[6] *Astr. Nach.* Nos. 3214, 3217; *Astr. and Astroph.* vol. xiii. p. 182.

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with a great telescope, a truly amazing appearance. Two nuclei separately catalogued by Sir John Herschel are then seen to be connected by an exterior faint sweep from an inner system of wreathing nebulous bands. These, too, show nodosities and angularities,[1] in obvious mutual relations, as if the knots, instead of simply forming upon the spires, had determined, or at least deflected their course. A still clearer knowledge of their arrangement was gained through a photograph taken by Dr. Roberts with four hours' exposure, April 28, 1889.[2] The nebula displayed itself, no longer simply coiled like a watch-spring, but as composed of a pair of curving arms issuing from opposite extremities of an oval central body. One of these loses itself in a vague effusion, as a comet's tail dies out into darkness; the other attains the secondary nucleus, and there terminates. The spiral character of this great vortex is perhaps rendered exceptionally conspicuous by its being more favourably placed than most others for our inspection. We seem to get nearly a bird's-eye view of it, and are thus enabled to take in the design of its construction at a glance. Its spectrum is continuous.

An object in Virgo 3′ across (M 99) is a right-handed spiral. Its branches turn the opposite way from those of M 51. Their tendency to form nodes and angles was strikingly shown in a photograph obtained in two hours, by M. von Gothard, April 12, 1888.[3] A diffuse nebulous mass in Triangulum (M 33), just discernible to the naked eye, appeared with the Rosse reflector in the guise of a "large spiral, full of knots."[4] Since it measures 62′ by 35′, its real size must be prodigious, and its structural details are of corresponding intricacy.[5] Fundamentally, however, the nebula, like all other known members of its class, doubtless consists of a nucleus and two winding branches, the complex ramifications of which are of what may be called incidental origin. A photograph of it, taken by Dr. Max Wolf, September 26, 1902, is, with his kind permission, exhibited in Plate XIII., Fig. 2.

Curved furrows of light and shade, concentrically disposed,

[1] Vogel, *Publicationen*, No. 14, p. 32.
[2] *Celestial Photographs*, vol. i. p. 85.
[3] Vogel, *Astr. Nach.* No. 2854. [4] *Phil. Trans.* vol. cli. p. 711.
[5] Roberts, *Celestial Photographs*, vol. ii. p. 85.

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are a surprisingly persistent feature of the nebular multitude. Most of those photographed by Professor Keeler in 1899 disclosed this species of conformation;[1] and it is, as a rule, prominently apparent in "spindle" nebulæ despite extensive foreshortening. These are believed to be flat discs, seen more or less obliquely, and constituting, when their planes actually coincide with the line of sight, those elusive objects designated by Swift "hair-line" nebulæ.[2] Spiral proclivities appear, in fact, to characterise, in some degree, every form of cosmical agglomeration, and depend no doubt upon laws prescribed for their development foreign to terrestrial experience.

The tendency of winding nebulous bands to become *knotted* often proceeds so far that the knots all but completely absorb the bands.[3] Multiple groups of nebulæ then appear ranged along curved lines, the intermediate faint luminosity becoming perceptible only with large telescopic apertures. Such is the curious double nebula in Perseus (M 76), noticed by the present Lord Rosse, to constitute, with subordinate nodules and streamers, a system modelled on a "reaping-hook" pattern.[4] A gaseous spectrum is derived from it. Similar combinations are met with in the southern constellation Mensa (N.G.C. 2046), where five nebulæ are disposed along an oval line, and in a "falcated" nebula with three knots situated in Cepheus (N.G.C. 7008).

All the diversities of double stars, it was pointed out by Sir John Herschel,[5] "have their counterparts in nebulæ; besides which, the varieties of form and gradation of light in the latter afford room for combinations peculiar to this class of objects." Its members are surprisingly numerous, one in sixteen of the 5079 nebulæ catalogued by Herschel in 1864 having a companion, usually of the condensed spherical kind. Most of these compound objects are, nevertheless, photographically resolvable into bi-nuclear spirals.[6] Yet the possibility is not excluded that true binary nebulæ may subsist, and eventually give signs of slow mutual revolution.

A nebula in Ursa Major (N.G.C. 3690) divided by Swift

[1] *Astr. Nach.* No. 3601. [2] *Monthly Notices*, vol. lviii. p. 331.
[3] Cf. a set of photographs by Dr. Roberts, *Knowledge*, vol. xx. p. 53.
[4] *Trans. R. Dub. Soc.* vol. ii. p. 21.
[5] *Outlines of Astr.* p. 647. [6] *Astroph. Journ.* vol. xi. p. 347.

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in 1885,[1] makes probably the closest pair known; and a curious reproduction, with greatly widened spatial intervals, of star systems like that of γ Andromedæ, occurs in a triple nebula in Virgo, consisting of a bright round nebula attended, at a distance of 5′, by an extremely faint one which is itself double[2] (N.G.C. 5813-14). Another compound object of a striking character was noticed by Sir John Herschel[3] in Canes Venatici (N.G.C. 4631), where an enormously long ray of nebulosity has a round, dimly luminous companion, a tenth-magnitude star placed between serving perhaps as a centre of attraction for both. In other cases, the systemic association of individual stars and nebulæ seems tolerably obvious. Merope in the Pleiades, as we have seen, claims the attendance of a hazy satellite; and Dr. Swift observed at Echo Mountain an apparently quadruple star to be really composed of two pairs, 4″ apart, each consisting of a star and nebula.

A very close double nebula in Gemini (N.G.C. 2371-72) has also an intervening star symmetrically located in the line joining their centres.[4] Cirrus-like streaks of nebulosity partially encircle the two objects. Duplicity is, in other cases, still less clearly defined. Thus, a pair of nebulæ near γ Leonis (N.G.C. 3226-27) are together enclosed in a faint luminous envelope, the effect recalling that of the celebrated "Dumb-bell" nebula in Vulpecula (M 27),[5] which is only perceived to be essentially single when the "neck" uniting two conspicuous hazy masses is brought into view with a powerful telescope. Sir John Herschel first observed the elliptical outline of the entire to be rounded out by faint luminosity, and thus saw it in its true aspect as a large, diversified oval disc, measuring about 5′ by 8′. It might indeed be called a magnified planetary nebula not devoid of annular inclinations. The eventuality that by the progress of the central contraction and marginal spreading indicated by its present hour-glass shape, the chief part of its mass may become diffused into a ring, is strongly

[1] *Sid. Mess.* vol. iv. p. 39.

[2] D'Arrest, *Astr. Nach.* No. 1369. [3] *Phil. Trans.* vol. cxxiii. p. 431.

[4] Lassell, *Memoirs R. Astr. Soc.* vol. xxiii. p. 62; Lord Rosse, *Phil. Trans.* vol. cxl. p. 512.

[5] D'Arrest, *Abhandlungen*, Leipzig, 1857, p. 325.

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suggested by the analogy of the bright spots at either end of the minor axis of the ring-nebula in Lyra. A planetary in the southern hemisphere (N.G.C. 1365) appears, in fact, to have already reached a more advanced stage on the same road, and several "miniatures" of the "Dumb-bell" are included among that class of objects. One especially in Cygnus (N.G.C. 6905), depicted by Vogel with the Vienna 27-inch, easily gives an impression of actual duplicity,[1] and showed at Parsonstown as a "beautiful little spiral." It has a central star and four "satellites." Its visual spectrum, like that of the Dumb-bell nebula, is approximately monochromatic. The leading nebular ray at 5007 concentrates nearly the whole of its light.

A photograph of the Dumb-bell nebula, taken by Dr. Roberts with an exposure of three hours, October 3, 1888, intimates pretty clearly the advance towards completeness of the oval bright border of the disc,[2] as well as its superposition upon a fainter, more elliptical one, visible as a kind of effusion at the extremities of its longest diameter. Vogel's drawing[3] likewise suggests, though after a different fashion, the presence of two ellipses, one partially concealed behind the other; and there hence seems reason to think that this singular formation partakes in more ways than one of the compound character evident in many planetary nebulæ. Nor is it perhaps isolated in space. On Professor Schaeberle's plates it appeared as the bright central part of a right-handed vortex; cosmical relations being thus ascribed to it no less extensive than those claimed, on similar evidence, for the spiral Ring in Lyra.

[1] *Publicationen*, Potsdam, No. 14, p. 36.

[2] Rabourdin, *Comptes Rendus*, t. cxxvi. p. 380, commented on the analogy between the Dumb-bell and the Lyre nebulæ rendered manifest by the Meudon photographs.

[3] *Publicationen*, No. 14, p. 35.

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CHAPTER XX

THE GREAT NEBULÆ

THE elliptical and irregular classes of nebulæ are illustrated by such splendid examples, that an entire volume rather than a single chapter might well be devoted to their consideration. One member especially of each towers above the rest, like Ajax among the Argive host, and the two are so different that it is not easy to award the palm of superiority to either. Needless to say that we allude to the objects in Andromeda and Orion, the types respectively of the elliptical and irregular plans of nebular construction.

The former (M 31) is the only genuine nebula which could easily be detected, without previous knowledge of its existence, with the unaided eye, and it is the only one, accordingly, which was discovered in pre-telescopic times. Al Sûfi was familiar with the "little cloud" near the most northern of the three stars in the girdle of Andromeda;[1] and its place was marked on a star-map brought from Holland to Paris by De Thou, and believed to date from the tenth century.[2] Simon Marius, who was the first to turn a telescope upon it, December 15, 1612, called it "stellam quandam admirandæ figuræ," and compared its dull and pallid rays to those of a candle shining by night through a semi-transparent piece of horn. Yet this strange phenomenon was only rescued from neglect by Boulliaud, whose attention was directed to it by the passage of the comet of 1664 across that part of the sky. So surprising did the disregard of it by Hipparchus, Tycho,

[1] Schjellerup, *Description des Étoiles*, p. 120.
[2] Le Gentil, *Mémoires de l'Acad.* 1759, p. 459.

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and Bayer then appear to him that he concluded it to vary in light, a hypothesis which derives no support from recent observations.

With powerful light-concentration this "most magnificent object" (in Sir John Herschel's phrase) assumes vast proportions. They were extended by G. P. Bond, using the 15-inch refractor of Harvard College, to cover an area of $4° \times 2\frac{1}{2}°$, and he probably did not reach their absolute limits. Two adjacent nebulæ, one (M 32) described by Le Gentil in 1749, the other (N.G.C. 205) by Caroline Herschel in 1783, "undoubtedly fall within their compass."[1] The light of this nebula is "of the most perfectly milky, absolutely irresolvable kind."[2] It does not collect into "floccules," and produces none of the scintillating effect giving to many gaseous nebulæ a delusive appearance of resolvability. From the circumference towards the centre, however, it gradually brightens, then abruptly condenses to a small nucleus, of indistinct outline under high magnifying powers, and possibly (like the nuclei of many comets) granulated, but assuredly not stellar.

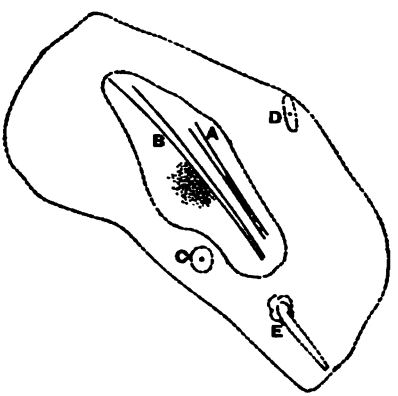

FIG. 32.—Structure-lines of the Great Nebula in Andromeda (*Knowledge*, vol. xii. p. 75).

This progressive brightening inward shows, nevertheless, interruptions. On September 14, 1847, Bond discerned two long dark rifts running nearly parallel to one another, and to the axis of the nebula.[3] Their detection was a consequence of the widened area of luminosity perceptible with his instrument, the inner rift having been taken, until then, for its boundary in that direction. The outlines of Bond's drawing are given in the accompanying diagram by Mr. Wesley (Fig. 32), in which the "rifts" are marked A and B. C represents Le Gentil's

[1] Bond, *Memoirs Amer. Acad.* vol. iii. p. 83.
[2] J. Herschel, *Memoirs R. Astr. Soc.* vol. ii. p. 496.
[3] *Memoirs Amer. Acad.* vol. iii. p. 80.

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D Miss Herschel's attendant nebula, E an exceptionally lucent region crowded (it has since been found) with hosts of minute stars.[1]

These enigmatical appearances at last assumed an intelligible form in a photograph taken by Dr. Roberts, October 1, 1888.[2] The view given by this magnificent picture of the Andromeda nebula as a symmetrical, though still inchoate structure, ploughed up by tremendous, yet not undisciplined forces, working harmoniously towards the fulfilment of some majestic design of the Master Builder of the universe, is of a nature to modify profoundly our notions as to how such designs obtain their definitive embodiment. An impression obtained three months later with four hours' exposure was carefully studied by Mr. Wesley; and his tracing of the lines of conformation brought out on the sensitive plate is copied in Fig. 33.

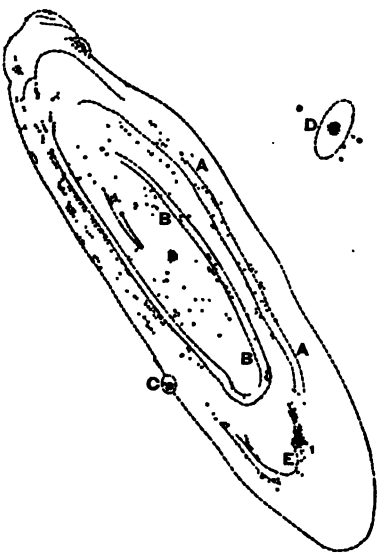

FIG. 33.—Spiral Structure of the Great Andromeda Nebula (*Knowledge*, vol. xii. p. 76).

Bond's "canals" are now seen prolonged and curved into two vast rings (AA and BB), which prove, on attentive consideration, to be dusky intervals separating the successive spires of a single great stream of nebulous matter, winding outward from near the primary to reach the secondary nucleus (M 32). The similarity of the relations between the two nuclei here, and in the "whirlpool" nebula in Canes Venatici, can scarcely escape notice. Thousands of stars are scattered over and around the Andromeda nebula; the situation of which in a prolongation of the Milky Way perhaps sufficiently explains their profusion. A beautiful photograph of it taken by Dr. Max Wolf, August 18, 1901, with the 16-inch Bruce lens,

[1] Ranyard, *Knowledge*, vol. xii. p. 76.
[2] *Monthly Notices*, vol. xlix. pp. 65, 120.

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is shown in Plate XIII., Fig. 1; and several striking pictures of the same marvellous object have been obtained by Mr. Ritchey with a two-foot reflector of his own construction. Near the centre on the original negatives, he tells us,[1] "sharply defined narrow rifts and dark holes" are distinguishable, all traces of which evade direct telescopic observation. These peculiar effects of chiaroscuro are probably indicative of tumultuary local movements, but attempts to explain them in detail must long remain futile.

Opinions are divided as to the constitution of the Andromeda nebula. Sir Norman Lockyer inferred it to be meteoric, comparing its state to that of "a comet within a month of perihelion."[2] Dr. Scheiner, on the other hand, regards it as virtually a cluster of sun-like stars.[3] A spectrographic impression, wrung from it by means of an exposure of 7½ hours with a short-focus reflector in January 1899, seemed to him a faint replica of the solar spectrum, marked by the familiar dusky rulings, but by no bright lines. Yet Sir William and Lady Huggins have more than once, observing the same spectrum visually, caught unequivocal traces of the admixture in it of emissive with absorptive elements.[4]

The real shape of the formation must be that of a disc, oval or round, but with a spheroidal mass both at the origin and extremity of the nebulous spires. Their convolutions, if actually circular, must lie in a plane inclined about 25° to the line of sight;[5] but we can only estimate their extent in space by making a precarious assumption as to their remoteness. Taking the distance of the nebula, for instance, to be of sixty-five light years, that already attributed, for illustrative purposes, to the cluster in Hercules, we find its radius to measure 162,000 times the radius of the earth's orbit; so that the frontier of this glimmering realm, as determined by Bond, is much more than half as remote from its centre as the nearest fixed star (α Centauri) is from ourselves! In travelling from end to end of it, light spends nearly six years; and if it

[1] *Astroph. Journal*, vol. xiv. p. 228.
[2] *Observatory*, vol. xii. p. 98. [3] *Astr. Nach.* No. 3549.
[4] *Atlas of Stellar Spectra*, p. 125.
[5] Scheiner, *Photographie der Gestirne*, p. 332.

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North.

1.

North.

2.

Photographs of Spiral Nebulæ. By Dr. Max Wolf.

Fig. 1. Great Nebula in Andromeda. Fig. 2. Spiral in Triangulum (M 33).

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lie obliquely towards us, then our view of the further margin may be of an earlier date than our view of the hither margin by a couple of years or more. Extensive changes within the nebula might then manifest themselves to us successively, although they had really occurred simultaneously; while, conversely, the coincidence in time of widespread variations would argue a position of the nebula nearly square to the line of sight. That it is still in the plastic stage there can be little doubt; and the outbreak of the "new star" of 1885 has shown that the action of the powers engaged in moulding it to its predestined shape may occasionally be attended by a catastrophic liberation of energy.

Two adjacent nebulæ in Leo, both enrolled by Messier, have finally quitted the ambiguous position long occupied by them. They are elliptical spirals, analogues of the colossal structure in Andromeda. Photographed by von Gothard in 1888, the one (M 65) showed a bright centre with four appendages resembling the sails of a windmill; the other (M 66), a complex arrangement of envelopes partially surrounding a nucleus, somewhat like the paraboloidal veils flung round the head of a comet near perihelion. These, however, were incomplete views. On Dr. Roberts's plates,[1] both objects took shape as ovoid formations composed of closely winding luminous coils, "thick inlaid," in the case of M 66, the chief of the pair, with nebulous condensations.

Sir John Herschel frequently noticed an approach to annularity in the members of this class of nebulæ, and added the remarkable comment that "as the condensation increases towards the middle the ellipticity of the strata diminishes."[2] This, if verified, would imply their ovalness to be not a purely visual effect; and the inference that the appearance of elongation corresponds to its reality is supported by such critical circumstances as the situation of a pair of stars either at the foci of a nebulous ellipse (N.G.C. 6595), or at the extremities of its major axis (N.G.C. 6648).

The longitudinal clefts often visible in ray-shaped nebulæ corroborate this opinion. For otherwise, why should they run lengthwise rather than in any other direction? If the bodies

[1] *Celestial Photographs*, vol. ii. p. 75.
[2] *Cape Observations*, p. 22.

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they characterise were, in fact, circular discs, none of their physical features could have any relation to the appearance they happen to assume by projection. Such a relation is extremely conspicuous in an elliptical nebula in the Centaur (N.G.C. 5128), divided along its entire length by "a perfectly definite, straight cut, 40″ broad." A delicate nebulous streak runs between, and parallel to the halves, which are sharply bounded on the sides facing each other, but hazy on those averted. "The internal edges of this very problematic object," Sir John Herschel remarked, "have a gleaming light like the moonlight touching the outline in a transparency."[1] It is by no means a solitary example. A long, narrow nebula in Leo (N.G.C. 3628) is "split into two parallel rays."[2] A black chasm, into which the nucleus protrudes, separates a lucid from a faint streak in Coma Berenices[3] (N.G.C. 4565); and a nebula in Andromeda (N.G.C. 891), with "a chink in the middle and two stars," supposed by Sir John Herschel to be "a thin, flat ring, of enormous dimensions, seen very obliquely," and photographed under that aspect by Dr. Roberts in 1891,[4] may really belong, as was indicated by the Parsonstown observations, to the numerous category of *cloven rays*. That their distinctive peculiarity depends upon some general constructive principle cannot readily be doubted, but we should vainly attempt to speculate upon its nature.

No descriptive formula is wide enough to include all the capricious forms of "irregular" nebulæ. In regarding these singular structures, we seem to see surges and spray-flakes of a nebulous ocean bewitched into sudden immobility; or a rack of tempest-driven clouds hanging in the sky, momentarily awaiting the transforming violence of a fresh onset. Sometimes, continents of pale light are separated by narrow straits of comparative darkness; elsewhere, obscure spaces are hemmed in by luminous inlets and channels. The "great looped nebula" (30 Doradûs), one of the inmates of the greater Magellanic Cloud, resembles a strip of cellular tissue. It serves not to conceal, but to ornament in a wide, openwork

[1] *Cape Observations*, pp. 20, 105.
[2] *Trans. R. Dub. Soc.* vol. ii. p. 95. [3] *Ibid.* p. 118.
[4] *Celestial Photographs*, vol. i. p. 41.

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Photograph of the Looped or "Spider" Nebula.
Taken with the Victoria Telescope, Cape Observatory, Jan. 29, 1903.

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pattern the sky behind it, and was described by Sir John Herschel as "an assemblage of loops," the "complicated windings" of which constitute it "one of the most extraordinary objects which the heavens present."[1] It gives, nevertheless, a dense photographic image. Plate XV. reproduces an admirable picture obtained in two hours at the Royal Observatory, Cape of Good Hope, in which claws and tentacles of faintly lucent stuff are seen to be thrown abroad in all directions from the main trunk, itself extensively riddled with dark spaces.[2] From the Arequipa plates Professor Pickering judged this object to be the core of a spiral,[3] probably embracing the whole contents of the Nubecula Major, and even to the eye it appears as in some sort their kernel. The "looped nebula" may then very well be the hub of its own particular universe. Its spectrum is gaseous, but with an unusually strong intermixture of continuous light.

The efficiency of the camera in disclosing the intricacies of nebular structure is vividly exemplified in Plate XIV., which exhibits, self-portrayed, one of the many celestial marvels gathered together in the constellation Cygnus. The object (N.G.C. 6992), though very imperfectly characterised to visual observation, is marked in our picture (the original of which was taken by Mr. W. E. Wilson of Daramona, October 7, 1899) by a surprising wealth of detail. Its texture is perceived to be throughout delicately filamentous,[4] the filaments being, as it were, drawn out in the same general direction; and the bright patches composing the nebula have besides, as Mr. Wilson noted, a parallel trend which coincides with that of the separate nebulous threads. A concordant play of forces is thus evidently brought to bear upon the entire formation, which, measuring from end to end 80′ of arc,[5] must be of a vastness transcending imagination. There is, besides, some reason to believe it organically related to an undulated nebular mass in its immediate neighbourhood (N.G.C. 6990).[6]

[1] *Cape Observations*, p. 12.
[2] Gore, *Worlds of Space*, p. 208.
[3] *Harvard Annals*, vol. xxvi. p. 206.
[4] See also Ritchey, *Astroph. Journ.* vol. xiv. p. 228.
[5] Roberts, *Cel. Photographs*, vol. ii. p. 145.
[6] H. C. Wilson, *Pop. Astr.* Oct. 1902.

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But all other irregular nebulæ sink into insignificance compared with that shown by an opera-glass as a silvery patch round one of the stars in Orion's sword. This extraordinary object (M 42) has been under effective observation for 250 years, and during the last eighty has been monographed, mapped, measured, figured, and photographed with a diligence worthy of its pre-eminence. Hence, future changes in it, should they take place, must be slight indeed to escape detection.

The multiple star θ Orionis might be called the foundation-stone of the edifice. All the lines of its architecture are laid down with reference to it, and the intimate physical association of the stars with the gaseous stuff surrounding them, has been spectrographically demonstrated by Sir William and Lady Huggins, and amply ratified by Professors Frost and Adams.

Surrounding the trapezium is the brightest part of the nebula, called, from its first delineator, the "Huygenian region." Over this space, shaped like a right-angled triangle, the light is collected into "flocculent masses," which, with the best seeing, prove to be throughout of a "hairy" texture. The effect was compared by Sir John Herschel to the "breaking-up of a mackerel-sky, when the clouds of which it consists begin to assume a cirrous appearance,"[1] and suggested to Mr. Lassell[2] "large masses of cotton-wool packed one behind another, the edges pulled out so as to be very filmy." The "pea-green colour" of the whole object struck him forcibly, but is apparent to most observers as little more than a greenish tinge.

Emanations (or what seem such) from the Huygenian core stretch away in wide curves to form the outlying portions of the nebula. One great effluence runs out into a "proboscis" attached to the upper jaw of the nondescript creature limned, in unearthly radiance, on the sky. Another, representing the lower jaw, bounds on the northern side the chasm of the distended fauces (the "Sinus Magnus"), and is subsensibly connected—as if by a shoal leading to an island—

[1] *Memoirs R. Astr. Soc.* vol. ii. p. 491; O. Stone, *Publ. Leander M'Cormick Observatory*, vol. i. pt. 7, p. 274.

[2] *Ibid.* vol. xxiii. p. 54.

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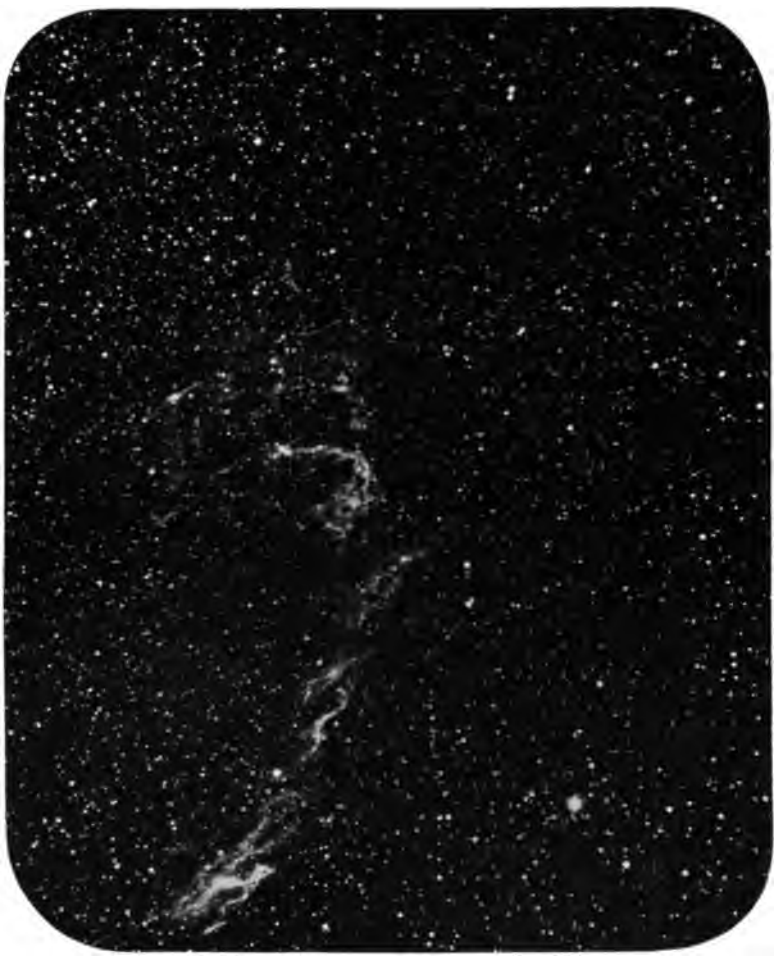

An Irregular Nebula in Cygnus. Photographed by W. E. Wilson, F.R.S

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with the "nebula minima" (M 43), a rounded mass which "appears as if just drawing together into a star."[1] Behind, and between the two, misty effusions spread far afield; resolved by G. P. Bond into an intricate fabric of convoluted and branching filaments, the brighter region from which they spring displaying a similar, but more compact mode of aggregation. "It is now impossible," he wrote after a particularly fine view of the nebula, on February 26, 1861, "to see it in any other aspect than as a maze of radiating, spiral-like wreaths of nebulosity, or filamentous tentacles, the centre of the vortex being about the trapezium."[2] And to Mr. Safford, using the then recently constructed 18½-inch Clark equatoreal, it appeared as "an assemblage of curved wisps of luminous matter, which, branching outward from a common origin in the bright masses in the vicinity of the trapezium, sweep towards a southerly direction, on either side of an axis passing through the apex of the Regio Huygeniana."[3]

The application of photography to this amazing object has not only supplied records of its actual condition indefinitely more authentic than any producible by the human hand, but has served to combine the peculiarities of its conformation into a strikingly suggestive whole. The outcome can best be appreciated by reference to Fig. 34, exhibiting an "index diagram" prepared by Messrs. Ranyard and Wesley from several negatives procured by Dr. Roberts with varied exposures. Two points are made perfectly clear by it. First, that the whole fabric of the nebula is concave towards an axis "passing through the trapezium in a north-easterly and south-westerly direction."[4] Next, that the effluences from the trapezium have a predominant tendency to assume ramified, or tree-like forms. Thus the seemingly eruptive jet marked with the letter *b* mimics the shape of a stone-pine, and bears a less equivocal resemblance to the "stemmed" type of solar prominences, as well as to certain arboreal structures visible in some photographs of the solar corona. The latter analogy is rendered still more apparent by comparing the vast nebulous out-growths, *e* and *h*, with the group of coronal rays repre-

[1] J. Herschel, *Memoirs R. Astr. Soc.* vol. ii. p. 495.
[2] *Harvard Annals*, vol. v. p. 158. [3] *Ibid.* p. 169.
[4] Ranyard, *Knowledge*, vol. xii. p. 147.

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sented in Fig. 35. The same kind of structures seem, in both cases, at once to spring upward and to curve inward, as if under the influence of a two-fold action—outward from a centre, and inward towards an axis. This organic similarity —first detected by Mr. Ranyard—between the Orion nebula and the luminous appendages of the sun, is borne out by the resemblance to spun glass of their minute texture.

The limits of the great "sword-handle" nebula are con-

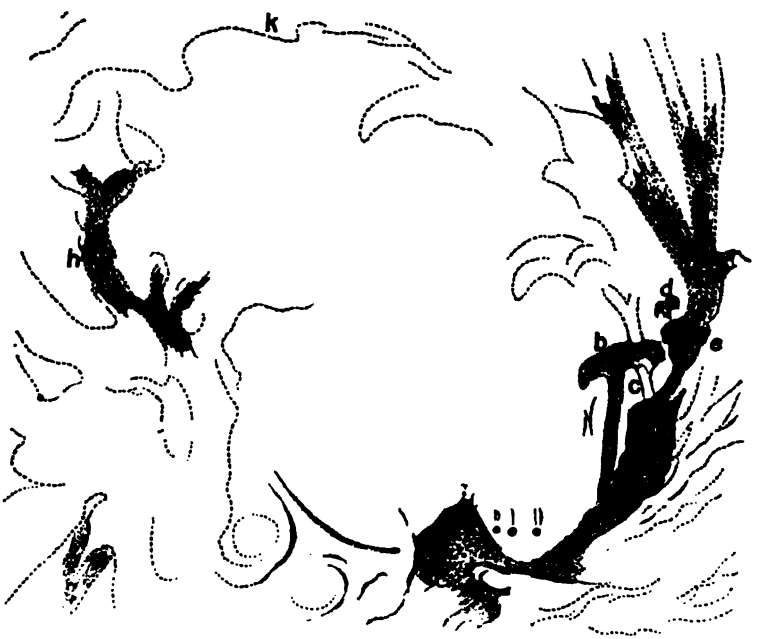

FIG. 34.—Index Diagram to Structures photographed in the Orion Nebula (*Knowledge*, vol. xii. p. 146).

tinually being pushed further back, and there is no reason to believe the process nearly terminated. On Mr. Roberts's plates,[1] first the "nebula minima" was joined on to the main body, then, with lengthened exposures, a cloudy mass to the north (N.G.C. 1977) was reduced to its true position of an offset, by which the forms of the parent-body are pretty closely counterfeited.[2] But even the combined object is far

[1] *Monthly Notices*, vol. xlix. p. 296.
[2] Ranyard, *loc. cit.* p. 148.

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from representing the nebulous contents of this part of the sky. Over an area of 150 square degrees, in which it is nearly central, twelve new nebulæ were photographed at Harvard College in the spring of 1888, and indications were obtained that Sir William Herschel's surmise[1] of the union into one immense stratum many degrees in length of the "great" nebula with others lying north and south of it, might be verified in the immediate future.[2] It was soon afterwards more than verified. On January 14, 1890, Professor W. H. Pickering exposed a plate during $6^h\ 22^m$ at the

Fig. 35.—Group of Coronal Structures (W. H. Wesley, *Knowledge*, vol. xii. p. 147).

summit of Mount Wilson, California, with a $2\frac{1}{2}$-inch portrait-lens. A singular disclosure resulted.[3] A great "snake" of diffuse nebulosity (as Professor Wolf has since called it), issuing from the trapezium, was perceived to enclose the whole central part of the constellation with dim folds 15 degrees in diameter. Cosmical vortices on this gigantesque scale are beginning to appear less rare phenomena than the strangeness of their aspect and implications might have led us to anticipate. They are discoverable only by means of short-focus photography.

In the Orion nebula we perhaps see an undeveloped

[1] *Phil. Trans.* vol. lxxix. p. 249.
[2] *Harvard Annals*, vol. xviii. p. 117. [3] *Ibid.* vol. xxxii. p. 36.

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cluster on the model of the Pleiades. Nearly a thousand stars were catalogued by Bond in the portion of it (3·36 square degrees in area) examined by him, and his list proves to be far from exhaustive.[1] Many of them should, indeed, in Professor Holden's opinion,[2] be accounted rather as nebular condensations than as true stars; but that they will eventually grow to be such, as they slowly absorb the nebulous material now enshrouding them, is a justifiable conjecture. The same process appears already far advanced in the Pleiades, with the result that the stellar now altogether predominates over the nebular element in the compound system. It may not have been always so. The balance inclined perhaps, in the remote past, as decisively the other way as it now does in the Orion nebula. The variability of nearly a hundred of its involved stars is an additional feature of resemblance to compressed clusters. Noted in a few cases by Dr. Roberts in 1890,[3] it was rendered astonishingly prominent in 1904, by Miss Leavitt's comparisons of records stored in the Harvard photographic archives.[4] The discovery gains added significance from the fact that many, or most of the twinkling crowd thus brought into evidence belong to the cluster-type of variables.[5]

It is not easy, Sir John Herschel tells us, "for language to convey a full impression of the beauty and sublimity of the spectacle offered by the Argo nebula, when viewed in a sweep, ushered in as it is by so glorious and innumerable a procession of stars, to which it forms a sort of climax."[6] "Situated in one of those rich and brilliant masses, a succession of which, curiously contrasted with dark adjacent spaces, constitute the Milky Way between Centaur and Argo," its branches with their included vacuities cover more than a square degree, and are strewn by above twelve hundred stars. These, unlike the components of the trapezium-cluster, show no general tendency to vary in light. The peculiarity from which the Argo formation derives its current title of the

[1] Parkhurst, *Astroph. Journ.* vol. xx. p. 136.
[2] *Washington Observations*, 1878, App. i. p. 221.
[3] *Monthly Notices*, vol. l. p. 316.
[4] *Astr. Nach.* No. 3950; *Harvard Circulars*, Nos. 78, 79, 86.
[5] J. S. Hagen, *Astroph. Journ.* vol. xix. p. 344.
[6] *Cape Observations*, p. 38.

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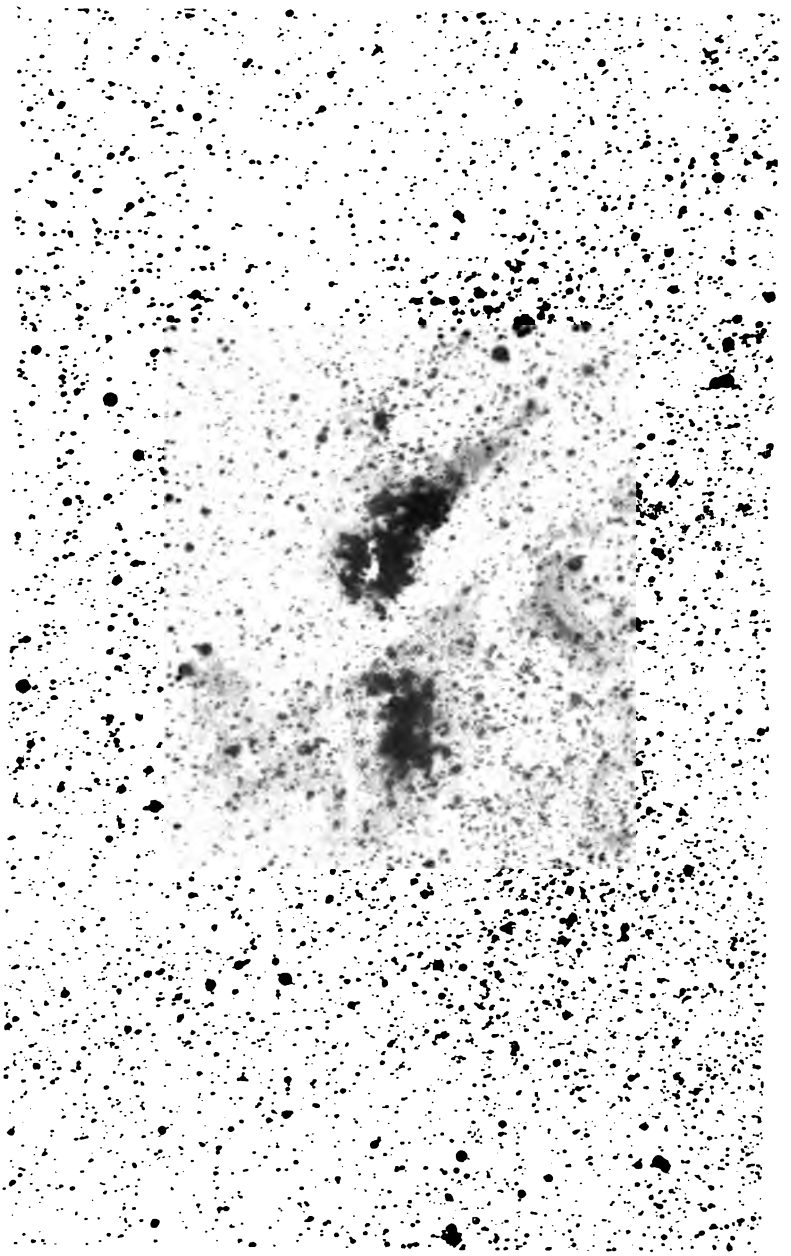

Photograph of the Key-Hole Nebula.
Taken with the Bruce 24-inch Refractor at Arequipa.

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"key-hole" nebula, is a large lemniscate-shaped opening in the central and brightest part, the blackness of which is qualified only by the veiling of one corner by a strip of thin nebulous haze. Four stars are placed precisely at the edges, none perceptible to the eye within the vacuity; and the famous variable η Carinæ, lies close to its eastern border. Such was the brilliancy of the star in 1838 that it almost obliterated the "key-hole," now, and previously to the outburst, the individualising feature of what would otherwise seem a chaotic sea of luminous billows. Duplication emphasises the meaning with which it is fraught. A second oval aperture, completely dark, but for the faint sparkle of four minute stars, occurs in the southern, sparser part of the nebula. It might be compared to the echo of a catch-phrase. Plate XVII. reproduces a photograph of this nebula, taken by Professor Bailey at Arequipa, June 1, 1896, with an exposure of four hours. The light and shade being reversed, the most intensely actinic parts of the portrayed object are printed black, while its vacuities are left white. Thus, the "key-hole" appears as a crooked, shadowless aperture in the most strongly luminous section of the inchoate structure, which is rendered in a manner bifid by a vast dusky channel running from south-east to north-west between two nebulous continents. The second "key-hole," which is larger than the first, and has some similarity to a kidney-bean, lies far to the south, in an outlying effusion.

A very peculiar gaseous nebula in Sobieski's Shield (M 17) has revealed itself piecemeal. Messier, first of all, noticed, in 1764, a spindle-shaped, starless ray, about 6′ in length. Sir William Herschel added an arch springing from its western extremity, and the combined object became known as the "Horseshoe" or "Omega" nebula, its form resembling that of the Greek capital letter Ω, with the left-hand base-line turned up obliquely.[1] Again, it suggested a "Swan" to observers whose instruments were inadequate to show the complete arch, and Flammarion compared it to a smoke-drift, fantastically wreathed by the wind. In the clear air of the Cape, Sir John Herschel detected a second very faint "horse-shoe," attached to the opposite end of Messier's streak from the first,[2]

[1] J. Herschel, *Phil. Trans.* vol. cxxiii. p. 461.
[2] *Cape Observations*, p. 10.

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and this new member seems to have been independently rediscovered by Swift, July 4, 1883.[1] A photograph of the Omega nebula, obtained by Dr. Roberts in 1893, exhibits Messier's ray as the axis of an oval mass covering an area 18′ by 12′;[2] but the intimate secret of its organisation has still to be penetrated. It is indeed situated too far to the south to be usefully investigated in these latitudes.

The "America" nebula is apparent only to the chemical retina. Some indications of its existence were caught by the elder Herschel; but its virtual discovery was made photographically by Dr. Max Wolf. On a plate exposed December 12, 1890, the vast object portrayed in Plate XVIII. emerged for the first time into full view, and received a name descriptive of its striking resemblance in shape to the continent of North America. Among the features attracting attention on our plate are a small, intensely black hole piercing the neck of light that corresponds to the Isthmus of Panama, and a nebulous star, like an island in the Atlantic Ocean off the coast of New Jersey. This is 57 Cygni, lately found to be a spectroscopic binary in swift circulation round an obscure companion.[3] It yields a helium spectrum in correspondence with its nebulous relationships.

No logical distinction can be established between irregular nebulæ and those indefinite tracts of milky radiance termed by the elder Herschel "diffused nebulosities." The total area of fifty-two separate tracts perceived to be thus phosphorescent, was estimated by him at 152 square degrees, and he added the judicious remark that "the abundance of nebulous matter diffused through such an expansion of the heavens must exceed all imagination."[4] The few visual observations subsequently made of these regions[5] intimate irregularities in their illumination doubtless dependent upon the slow advance of cosmic processes of large scope. Their investigation, however, is properly the task of the camera. Already, some of Herschel's "affected" regions have been proved, by the photo-

[1] *Sidereal Messenger*, vol. iv. p. 38. [2] *Cel. Photographs*, vol. i. p. 101.
[3] Frost and Adams, *Astroph. Journ.* vol. xvii. p. 381.
[4] *Phil. Trans.* vol. ci. p. 277.
[5] Dreyer, *V. J. S. Astr. Ges.* Jahrg. xxii. p. 62; Littrow, *Sterngruppen und Nebelmassen*, p. 29; Tempel, *Astr. Nach.* No. 2511.

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The America Nebula.
Photographed by Dr. Max Wolf, July 12-13 (*Knowledge*, vol. xxv. p. 156).

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graphs of Barnard,[1] Roberts,[2] and Wolf,[3] to include strongly developed nebulous formations; the condition of the rest has still to be ascertained. Prolonged exposures with appropriate instruments will be needed to determine it satisfactorily.

[1] *Astroph. Journ.* vol. xvii. p. 77.
[2] *Monthly Notices*, vol. lxiii. p. 26. [3] *Ibid.* p. 303.

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CHAPTER XXI

THE NATURE AND CHANGES OF NEBULÆ

SPECULATIONS as to an identity of nature between nebulæ and comets are no novelty; they presented themselves, as they could hardly fail to do, to the mind of Sir William Herschel,[1] and Sir Norman Lockyer sought to provide them with an experimental basis by his researches on meteorites in 1888-89.[2] The results were scarcely encouraging. Indeed, the two classes of bodies have spectroscopically little in common. No gaseous nebula gives a trace of the carbon-bands characteristic of comets; while the bright lines derived from nebulæ are absent from most comets certainly, from all probably. Yet a physical analogy subsists, and is evidently charged with meaning.

Both comets and nebulæ consist of enormous volumes of gaseous material, controlled by nuclear condensations, whether of the same or of a different nature in the two genera we need not now stop to inquire. Both, there is the strongest reason to believe, shine through the effects of electrical excitement. In both, there are manifest signs of the working of repulsive, as well as of attractive agencies.

A telescopic comet is indistinguishable except by its motion from the ordinary, centrally condensed, round nebula, which is itself indistinguishable from an exceedingly remote globular cluster. Superficial likenesses do not, it is true, count for much; one object may counterfeit another without bearing any true relationship to it. What it is really important to note is the structural resemblance of nebulæ to comets. The parts of a comet become differentiated exclusively

[1] *Phil. Trans.* vol. ci. p. 306. [2] *The Meteoritic Hypothesis*, p. 288.

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under solar influence. Hence their symmetrical arrangement, as regards an axis passing through the sun, is modified only by the orbital displacement of the body to which they belong, and from which they emanate. It is extremely curious to find that, notwithstanding the absence of these conditions, the features of certain nebulæ are impressed with a corresponding, though different kind of polarity. Definitely directed outflows (or what seem to be such) are in them of frequent occurrence.

From many of these objects, as from many comets, only a single stream of effusion is manifest; and we then get "stars with tails," which might well pass for miniatures of the bearded travellers through our constellations. These effusions are, in some cases, bounded by straight lines; they are fan-shaped; in others, they are curved, often so strongly that the "brush" is bent into a "coil." Such differences may be plausibly associated with the varied conditions of axial rotation in the star-like nucleus. Where there is none, the issuing matter naturally proceeds straight outward; its curvature depends upon its being left continually further behind in the widening circles reached by it as it ascends from an advancing point of efflux.

It is easy to see that this process, if carried far enough, will result in the production of a helicoidal nebula. Fully developed spirals are, however, constructed on a less simple principle. Their convolutions are duplex. Two opposing branches combine to form them. That these branches represent intakes of matter from space is hardly a tenable opinion. It has, in fact, been virtually abandoned owing to its inconsistency alike with the design and the details of the objects under consideration. The conviction is now dominant that they originated through some kind of repulsive action. Professor T. C. Chamberlin regards them as products of catastrophic disruption. Each is the wreck of a sun-like body, dispersed through the tidal influence of some similar orb to which it made a fatally close approach.[1] They illustrate, accordingly, "the effects of explosive projection combined with concurrent rotation." M. Deslandres adverts to the correspondence between the diametral wings of the solar corona and the opposed arms of a spiral nebula, the ramifications of

[1] *Astroph. Journ.* vol. xiv. p. 34.

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which he holds to be explicable on Brédikhine's theory of multiple cometary tails;[1] while Mr. W. E. Wilson was struck with the "cometary tails, curved like plumes away from the central nucleus," attached to the nodosities bestrewing his photograph of the Whirlpool in the Hunting Dogs.[2]

With very rare exceptions, nebulæ are seen by us, not in plan, but in perspective. "The only thing," Professor Holden wrote in 1889,[3] "we really know about the form of a nebula, in general, is that it is projected into a certain shape. The problem is to find the true curves in space, knowing only the projected curves." His efforts to solve this arduous problem by actual trials with helices of wire projected in all imaginable varieties of position, met with a certain measure of success. The "type-curve" at which he finally arrived, though not perhaps really conformed to in nature, served, at any rate, usefully to define ideas regarding "the actual situation of the different branches of a nebula in space of three dimensions."

Nebulæ of the spiral and "brush" kinds, are not the only ones exhibiting cometary relationships. A characteristic feature of nebulous trains and "wings," exemplified both in the Orion and Pleiades formations, is their vague diffusion on one side, but sharp termination on the other, just as in the luminous vanes appended to the heads of comets. The continued ejection of matter *against* a counter-current of force by which it is unceasingly driven backward, seems indicated in both cases.

Planetary nebulæ, too, imitate, in a fashion of their own, the heads of comets under energetic solar action. Their multiple discs correspond most strikingly to the multiple envelopes of comets, and intimate a similar origin through interior expansive or repulsive agencies. Only that in the absence of the directive power of the sun, the waves of emanation spread equally in all directions, producing successive approximately globular, instead of parabolic surfaces. Under the combined influences of rotation and contraction, such shells might be expected eventually to subside into rings;[4]

[1] *Comptes Rendus*, June 23, 1902.
[2] *Astr. Researches at Daramona.*
[3] *Publications Astr. Soc. of the Pacific*, vol. i. p. 25.
[4] Roche, *Mémoires de l'Acad. des Sciences*, Montpellier, t. viii. p. 244.

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but it would be rash to affirm that annular nebulæ, in point of fact, acquired in this way their present aspect.

No visible signs of movement have, up to this, been derived from nebulæ. In the ordinary sense they appear absolutely stationary. Accurate observations of them are, indeed, comparatively recent; they go back, nevertheless, far enough to justify the statement that not one among about four hundred well-determined nebulæ becomes progressively displaced by so much as one second of arc yearly. The nebulæ in the Pleiades ought perhaps to rank as exceptions to this general immobility, since we need no direct proof to assure us that they drift with the cluster of which they form an integral part. The drift, to be sure, is slow; but it is securely ascertained, and affords grounds for the sole estimate, that is not mere guess-work, of the distance of a nebulous system.[1] The apparent indifference of all other nebulæ to the perspective effects of the sun's swift advance through space leaves little probability that any of them lie as near to us as the nearer stars; and the probability is raised almost to certainty by the spectroscopic discovery that many of them are animated by rapid individual movements.

Thirteen planetary nebulæ measured by Professor Keeler in 1890,[2] proved to have an average radial velocity of 17 miles a second. The swiftest among them is the helical structure in Draco, which shows an advancing speed of 40 miles a second; the "Saturn" planetary in Aquarius also approaches the sun, though somewhat more slowly; while a stellar nebula in Aquila (N.G.C. 6790) increases its distance by 30 miles a second, or by ten times the earth's orbital radius in each year. As regards motion, then, no distinction can be drawn between stars and this kind of nebulæ. The irregular class has been investigated for spectral displacements only in its leading representative; and the concordant results of several inquirers prove the Orion formation to be in course of withdrawal from the earth at the rate of about 11 miles a second.[3] But, since this velocity must be largely, if not wholly, an effect of the sun's translation through space, the

[1] See *ante*, p. 106.
[2] *Lick Publications*, vol. iii. pp. 217, 228.
[3] Frost and Adams, *Astroph. Journ.* vol. xix. p. 354.

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nebula may in fact be almost at rest in the stellar system. Indications of possible movements within it were derived by Dr. Vogel in 1902 from spectrograms of its various parts;[1] and the clue will perhaps eventually be followed up to a definite issue. But no nebula has yet been proved, by line of sight measures, to rotate on an axis. Nor are double nebulæ perceptibly circulating. The systems they presumably constitute remain rigidly fixed. The contrary has often been asserted; yet revolutions, alleged on the strength of inexact observations, and brought to a standstill by precise ones, must plainly be dismissed as illusory; "unless," as Dr. Dreyer says,[2] "we are to believe that nebulæ in the good old days moved about as they liked, but have been on their good behaviour since 1861 and kept quiet." The existence, frequently observed, of a nebulous connection between grouped objects, intimates a state of things hardly compatible with mutual circulation. The relations of these imperfectly separated individuals are perhaps in a state of transition, like those of multiple cometary masses, at times enclosed together like double nebulæ, in a dimly luminous sheath.

The idea of the accompaniment of planetary nebulæ by satellites, was suggested to Sir John Herschel by the frequent and close proximity to such objects of minute stars,[3] and he recommended their careful micrometrical measurement as a criterion of possible future changes. But d'Arrest found the attendant stars just in the positions Herschel had assigned to them,[4] and only one case of suspected displacement has since attracted serious attention. Professor Barnard noticed a minute discrepancy between his measures in 1899 of a twelfth-magnitude star closely following the ring nebula in Lyra and those made by Burnham eight years previously.[5] He inclined, nevertheless, to attribute the alteration (if real) to a shifting of the point of reference rather than to movement in the star. Now the point of reference having been the nebular nucleus, the verification of his surmise would involve the detection of proper motion in a class of objects heretofore

[1] *Sitzungsberichte*, Berlin, March 13, 1902.
[2] *Monthly Notices*, vol. xlvii. p. 418. [3] *Phil. Trans.* vol. cxxiii. p. 500.
[4] *Leipzig Abhandlungen*, Bd. iii. p. 308.
[5] *Monthly Notices*, vol. lx. p. 245; cf. Leavenworth, *ibid.* vol. lxi. p. 25.

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imperturbably fixed. The lapse of a very few years will render practicable the decision of this interesting question.

Variability in light is a quality of nebulæ as surely as of stars, although the cases are rare in which it can be established with certainty. Nebulæ are peculiarly sensitive to atmospheric influences. Their finer details, always hovering on the verge of visibility, are completely shrouded by the lightest mist. Hence, even to the same eye, and with the same instrument, the aspect of the same nebula often varies greatly from night to night, and since personality is nowhere stronger than in the perception of the delicate luminous gradations delineating to our sight the forms of nebulæ, a difference of observers adds a further incalculable element of uncertainty. Rumours of change then easily arise, but are with difficulty substantiated.

They start, nevertheless, from a presumption not unwarranted by facts. The occurrence of luminous fluctuations in nebulæ has been proved by the complete extinction of one, and the fading to evanescence of a second in the same vicinity. On October 11, 1852, Mr. Hind discovered, near the group of the Hyades in Taurus, a small round nebula (N.G.C. 1555) with slight central condensation. It was then very faint, but brightened steadily until 1856, when d'Arrest ranked it as belonging to the first, although verging towards the second class of brilliancy.[1] His amazement then was extreme to find on October 3, 1861, its place apparently vacant! Some glimmer of its light was indeed made out for a year or two longer with the Pulkowa 15-inch refractor; but that too waned, and the object remained invisible for above a quarter of a century. Then, in 1890, it was just barely descried by Professor Barnard with the 36-inch Lick telescope; and even that superb instrument failed to show it in September 1895. In 1897 it was not to be seen on any terms; in 1898, it barely stained the field of the 40-inch Yerkes refractor; but Professor Keeler managed in 1899 to secure impressions of its somewhat complex form on long-exposed Crossley plates.[2] The apparition, so far as can be judged, was a strictly temporary one. Hind's notice probably did not

[1] *Astr. Nach.* Nos. 1366, 1689; Auwers, *ibid.* No. 1891.

[2] *Problems in Astrophysics*, p. 523 (Clerke).

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lag far behind its first perceptibility with moderate instruments.

A curious feature of the occurrence was the sympathetic, or at any rate simultaneous, decay in light of a small star—since known as "T Tauri"—placed almost in contact with the nebula. The star, however, recovered in 1868 about the same time that a second new nebula (N.G.C. 1554) came into view. First discerned by O. Struve, it was observed by d'Arrest, who was fully convinced of its novelty, and his opinion was borne out by its subsequent total disappearance.[1]

The light-changes of nebulæ do not offer the same diversity as those of stars. Only two kinds of variability — those producing respectively ephemeral appearances and capricious brightenings and fadings—are represented among them. No periodical nebulæ have yet been shown to exist. The influences, of whatever nature, bringing about the rhythmical pulsations of stellar light, would seem to be absent from the nebular kingdom. A distinction, however, peculiar to themselves, can be established among variable nebulæ. Their fluctuations may be either general or partial. They may affect the whole of a moderately compact object, or certain sections of an extensive formation. Examples of both kinds, and of all degrees of authenticity, abound; but we will only mention a very few, in which the reality of change seems scarcely disputable.

One such is afforded by an elliptical nebula in Leo (N.G.C. 3666), "very bright" when discovered by the elder Herschel in 1784, but noted by his son as abnormally faint for the first class. Subsequently observed alternations have made it all but certain that the discrepancy indicated genuine change.[2] A nebula in Cetus, too (N.G.C. 955), is evidently subject to similar vicissitudes. Schönfeld in 1861, and Vogel in 1865, failed to see it, although it was, at sundry other epochs, easily visible to the former observer, as well as to d'Arrest and Winnecke, and fully justified in 1887, Dr. Dreyer considered, Herschel's ascription of it to the second order of brightness.[3]

[1] Dreyer, *Memoirs R. Astr. Soc.* vol. xlix. p. 214.

[2] Winnecke, *Astr. Nach.* No. 2293; Dreyer, *Memoirs R. Astr. Soc.* vol. xlix. p. 218.

[3] Winnecke, *Monthly Notices*, vol. xxxviii. p. 104; Dreyer, *loc. cit.* p. 213.

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Burnham found it without difficulty in 1891, and attributes its occasional evasiveness to "unfavourable atmospheric conditions."[1] Yet they seem hardly adequate to explain the marked anomalies of its record.

Intrinsic change indubitably affects a small nebula attached in fan-shape to the variable star R Coronæ Australis. Suspected by Schmidt in 1865, it has been rendered patent by Mr. Innes's observations.[2] When further materials are available it will be of great interest to determine the relations in light-change of these dissimilar, though associated objects.

Again, one of a group of nebulæ in Virgo, observed by Schmidt at Athens in 1862 (N.G.C. 5655), could not be found by d'Arrest in 1865, two minute stars appearing as its *locum tenentes*.[3] If, as seems probable, the identical object was inserted by Herschel, from an observation of December 28, 1785, as No. 498 of his second class, its re-emergence to view may at any time be looked for. The collection to which it belongs, were judged by d'Arrest (no doubt rightly) to be the brightest "knots" of a wide-spreading nebulous structure (M 49). The variability of one of them approximates to the local changes of irregular nebulæ, exemplified with most certainty in the virtual effacement of the "swan" section of the formation in Argo. Prominent in Sir John Herschel's drawing, it was missed visually by Mr. H. C. Russell in 1871, and is very feebly represented in the best modern photographs. A bare mottling of the lacuna to the south-east of the "key-hole" in Plate XVII. now marks the place where the nebulous "swan" formerly paraded its radiant plumage.

No change so striking has, within two centuries, occurred in the Orion nebula. Its organisation appears, on the whole, to be wonderfully stable; for certain alleged light-fluctuations of a partial kind[4] have not been thoroughly substantiated.[5] Those believed to affect the Omega and Trifid nebulæ, seem to have resulted in a modification of what we may call *coast-lines*,

[1] *Lick Publications*, vol. ii. p. 172.

[2] *Annals Cape Observatory*, vol. ix. p. 134 B.

[3] D'Arrest, *Astr. Nach.* No. 1520.

[4] O. Struve, *V. J. S. Astr. Ges.* Jahrg. xix. p. 35; *Mélanges Math.* t. ii. p. 530; d'Arrest, *Astr. Nach.* No. 1366; Holden, *Wash. Observations*, 1878, App. i. pp. 121, 225.

[5] O. Stone, *Publ. Leander M'Cormick Observ.* vol. i. Plate VII. p. 274.

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here advancing, there encroached upon by the sea of darkness which surrounds them. In the latter object, a singular apparent alteration in the relative places of the multiple star and the nebulous masses involving it, is perhaps due to this instability of outlines. Sir John Herschel in 1827 and 1833 described the star as located "exactly in the central vacuity" of the nebula, and just at the point of convergence of the three rifts dividing it throughout.[1] But a drawing made by him at the Cape in August 1835 exhibits the star, no longer as central, but as adhering to the eastern mass of nebulosity. A similar state of things was noted by Mason and Smith in 1839,[2] and subsists so obviously at the present time, as to render a mistake about it inconceivable. The implied change, however, must have taken place abruptly, between 1833 and 1835, and then ceased; so that proper motion, either of the star or nebula, had certainly nothing to do with it.[3] There seems no alternative but to admit that the frontier-lines between luminosity and obscurity were, at the epoch in question, very considerably "rectified."

Speculation regarding the nature of white nebulæ must be left in abeyance until their spectra have been satisfactorily investigated; but there is a consensus of opinion that those showing a discontinuous radiance are luminous through electrical excitement. The fact of their incomparable tenuity was established by Mr. Ranyard in 1892, on the ground of their ineffectiveness in imparting motion to bodies in their vicinity; and highly rarefied gases in space cannot be *hot*. Gaseous nebulæ are, in fact, reasonably believed to be at a temperature not much above absolute zero. They are not, then, incandescent, but rather "luminescent"; their light is independent of thermal conditions. The phosphorescence produced in a Crookes's vacuum-tube exemplifies, according to M. Deslandres, their mode of illumination.[4] Cathode-rays emanating from central condensations set their materials aglow. M. Arrhenius, on the other hand, derives from exterior

[1] *Memoirs R. Astr. Soc.* vol. iii. p. 63; *Phil. Trans.* vol. cxxiii. p. 460; Holden, *Amer. Journ. of Science*, vol. xiv. p. 434 (1877).

[2] *Trans. Amer. Phil. Soc.* vol. vii. p. 175.

[3] Dreyer, *Monthly Notices*, vol. xlvii. p. 419.

[4] *Comptes Rendus*, May 20, June 23, 1902.

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agencies the light-stimulus acting upon them. There are many indications, he tells us,[1] that space is pervaded by negatively charged particles expelled with enormous velocity by the stars. These being absorbed by nebulæ, occasion electrical discharges through the gaseous volumes composing them, their frigid condition notwithstanding; and Professor Dewar's experiments assure us that excessive cold is no bar to light-emission. Moreover, none that is truly continuous seems to be included in nebular radiations. What passed for such has been analysed by Mr. Palmer into ranges of faint, superposed bright lines.[2] Associated stars, however, yield genuine stellar spectra, and have perhaps taken an active part in the weaving of the textures they begem. The unmistakable analogy, at any rate, between solar-coronal and cometary forms on the one side, and nebular forms on the other, indicates for all a kindred origin in the play of opposing forces, generated by certain foci of condensation, one of which is our sun, while the others can be safely designated only as nuclear points. Where there is only one such nucleus, the enveloping gases assume a simple globular or oval shape; where there are many, the result is exceedingly complex. Irregular nebulæ are thus most likely potential star-clusters; they consist of a stellar framework, draped with nebulous folds, spirals, and festoons, disposed along lines of force laid down by the rival or concurrent energies of the compact masses which it is permissible to regard as inchoate suns.

[1] *Lehrbuch der Kosmischen Physik*, Bd. i. p. 43.

[2] *Lick Bulletin*, No. 35. Inequalities of the kind were long ago suspected by Sir William and Lady Huggins.

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CHAPTER XXII

THE DISTANCES OF THE STARS

THE most arduous among the problems of stellar astronomy was, singularly enough, the first to be attacked. It was attacked, indeed, before the possibility was even remotely discerned that stellar astronomy might come to be regarded as a substantive branch of science. In the hope, not of penetrating the inscrutable secrets of the remote sphere of the fixed stars, but of solving doubts about the motion of the earth, Copernicus, Tycho, and Galileo led the way in the long series of experiments on the apparent displacements of the stars resulting from our own annual travelling round the sun. The interest of the question whether such displacements existed or not, was for them of a wholly "parochial" kind; it lay in the test they afforded as to the reality of the terrestrial revolutions. Should the stars be found to shift ever so little by the effect of perspective, then the heliocentric theory could no longer be gainsaid; if, on the contrary, they ignored sublunary circlings, the "pill" (as Kepler termed it) to be swallowed by Copernicans was indeed a huge one. For the distances to which the fixed stars had, in that case, to be relegated, seemed in those times monstrous and incredible; and monstrous and incredible they would appear still, were we not forced by irrecusable evidence to believe in them.

Throughout the history of these inquiries, at least in its earlier part, it may be taken almost as an axiom that the largest ostensible parallaxes were obtained by the worst means. With each successive improvement in methods and instruments, as the limits of possible error shrank, the displacements apparently measured dwindled, and the stars

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became less accessible to attempted determinations. During some three centuries, the ill-success of an astronomer in this matter was a measure of his skill and judgment. Results obtained with suspicious facility by inexpert observers utterly evaded the guarded scrutiny of such men as Tycho Brahe, Bradley, and Pond. Flamsteed, indeed, just at the close of the seventeenth century, detected in the pole-star annual variations which were certainly *not* illusory. Yet here too there was a *caveat*. Theory and fact did not correspond.

Let us consider for a moment what must be the visual effects upon very distant objects of the comprehensive and unceasing rounds of the planet upon which we are borne as spectators. Unmistakably, to begin with, we see them in different directions at different times of year. In January and July, in March and September, and so on, we are at opposite ends of base-lines 186 millions of miles in length. The stars then must be continually thrown, now a little to one side, now to the other, of the true, or "mean" places which they would severally occupy if viewed from the immobile sun. In other words, each describes round its mean place in a period of a year, a small apparent orbit, which is nothing else than the orbit of the earth projected in miniature on the sky. For stars situated in the ecliptic—that is, in the plane of the earth's motion—this orbit contracts into a right line, along which the star merely swings to and fro; for stars near the pole of the ecliptic, the perspective orbit is sensibly a circle; while intermediate latitudes afford all degrees of foreshortening. Every star—unless those few lying close to the pole of the ecliptic—has thus its epochs of maximum parallax, six months apart, when it seems to stand alternately at opposite extremities of the major axis of the parallactic ellipse, and it is then that measures of its apparent displacements can be most advantageously made. These opportune seasons occur when the earth's longitude falls short of, or exceeds by ninety degrees the longitude of the star. They are accordingly different for stars with different longitudes.

The precise *form* of displacement due to the earth's revolution round the sun is thus strictly calculable for each individual star; the *amount* alone cannot be predicted, but must be obtained by observation; and from this amount the distance of the star is deduced. For each parallactic orbit is a perfect model, both

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in shape and size, of the earth's orbit as it would be seen from the star, abridgment of compass (down to contraction into a virtual point) corresponding to a more and more profound immersion of the point of survey in the abysses of space.

The parallax of a star is then the difference between its positions as seen from either side, and from the centre of the earth's orbit. It is, in short, the angle subtended, at the distance of that particular star, by the mean interval between earth and sun. Now we can tell in a moment how far off a spectator must be to see a line ninety-three millions of miles in length diminished to the angular dimension of, let us say, one second. He must be 206,265 × 93 millions of miles distant. But no star has yet been found so *near* to us as this. That is to say, the shift of no known star amounts to as much as the width of a sixpence held up at Charing Cross to a spectator at Stanhope Gate or at Millbank.

We are now in a position to understand why it was that Flamsteed's observations of the apparent displacements of Polaris could not, when critically examined, be set down to the account of parallax. The star seemed indeed to describe, regularly each year, a little ellipse of exactly the right *shape*, and as to its *size*, there was no *à priori* reason why the pole-star should not have a parallax of upwards of twenty seconds. But there was one irreconcilable discrepancy. The displacements noted occurred at wrong times. Had they been of a parallactic nature, the position of the star in its minute fictitious orbit should have been invariably ninety degrees in advance of what it actually was. They were not then due to parallax; but obtained their proper explanation from Bradley's discovery of the aberration of light in 1729.

During the ensuing century and a quarter, the only valid results obtained in this direction consisted in demonstrations, renewed and enforced from time to time as more conclusive evidence presented itself, that with the instrumental means then available, stellar parallax was an inappreciable quantity. Bradley showed that it must fall short of half a second, and although his reasoning applied strictly to only a limited number of stars, it was rendered at once more general and more cogent by the investigations of Pond and Airy, of Struve and Bessel. It thus seemed that astronomers should content themselves

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with the knowledge that the stars were exorbitantly remote, so remote that light spent at least four or five years in travelling to us from the brightest of them, and might, for anything that appeared, need an indefinitely longer time for the journey. The labours and refinements of two centuries had issued in fixing a *lower* limit for distance, an *upper* limit for parallax; in isolating the sun from his compeers by setting between him and them an unmeasured stretch of desert space; in widening to a startling extent the boundaries of the visible universe. Kepler's "mighty bolus" had to be swallowed in its entirety.

At last, in 1827, Savary of Paris brought forward a method for fixing an *upper* limit to the distances, a *lower* to the parallaxes of binary stars moving in known orbits. The further off from us such orbits are, the greater of course their real size, and the longer the time taken by light to cross them. Hence, the deviations of the moving stars from their true places due to inequalities in light-transmission must increase with their remoteness, and thus serve in theory to determine the distance from the earth of the pair. Or if no such deviations are apparent, it should at least be possible to fix an amount which they could not exceed without becoming so. Savary, accordingly, professed to demonstrate in this way that ξ Ursæ Majoris, the couple most favourably situated for the purposes of the inquiry, must have a parallax exceeding $\frac{1}{300}$ of a second[1]—must, that is, be at a less distance than would be traversed by light in 1000 years. But the information, however credible in itself, was not fully authenticated. Villarceau showed, in 1878,[2] that the method was inapplicable except to stars of known relative masses; and it was by that time already obsolete. The light-equation in stellar orbits is too small to be extricated from errors of computation and observation, unless where the occurrence of eclipses sharply defines positions and epochs.

Besides, the end in view can now be compassed by spectroscopic means. Measures of radial velocity in an orbit of known inclination give at once its linear dimensions, and by comparison with micrometrical data, its distance from the

[1] *Conn. des Temps*, 1830, p. 169.
[2] *Ibid.* 1878, p. 68.

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earth;[1] and the possibilities of the method were illustrated by M. Bélopolsky's investigations of γ Virginis and γ Leonis in 1898.[2] Of considerably higher promise are the results derived by Professor Hussey for δ Equulei, and by Professor Wright for α Centauri; and those obtained for Castor by Dr. Curtis are of exceptional importance.

By-ways, however, may be neglected since the road leading straight to the goal has been made practicable. The engineer who carried it over the barrier long helplessly confronted, was Fraunhofer. The improvements effected by him in the power and perfection of telescopes, as well as in the application to them of micrometrical apparatus, alone rendered feasible the exquisitely refined measurements upon which the detection of stellar parallax absolutely depends.[3]

These measurements are for the purpose of determining variations in the angle between the star chosen as the subject of experiment and one or more "comparison-stars" in its neighbourhood, treated as fixed points of reference because assumed to be indefinitely remote. From progressive annual changes of the intervals separating them from the star they serve to test, the amount of its parallax, hence of its distance from the earth, is learned. But if the comparison-stars are themselves affected by sensible parallactic displacements, then the result is, to a certain extent, if not wholly vitiated. Should they chance, for instance, to be at the same distance from us as the compared object, then all the stars under observation will shift together, giving the effect of immobility, and implying the absence of measurable parallax, when in reality a large one may be present. Again, a parallax sought by the aid of a comparison-star itself possessing one-half the parallax of the star investigated, will come out only one-half of its true value. It may even happen that the comparison-star is, of the two, our nearer neighbour in space, when a "negative parallax" (as it is called) will emerge, showing how great the discrepancy is in the wrong direction.

It is, indeed, the weakness of the "differential method of

[1] Fox Talbot, *Report Brit. Ass.* 1871, pt. ii. p. 34; Rambaut, *Proc. R. Irish Acad.* vol. iv. p. 669; T. J. J. See, *Astr. Nach.* No. 3314.

[2] *Ibid.* No. 3510.

[3] C. A. F. Peters, *Zeitschrift für populäre Mittheilungen*, Bd. iii. p. 96.

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parallaxes" that it gives relative, never absolute results. Not only does some degree of doubt always attach to them, but their deviations from the truth are always on the same side. They tend in all cases to diminish the parallax, and exaggerate the concluded distance. Nevertheless, the advantages of the method are so overwhelming, it abolishes so many causes of error, and strikes at the root of so many illusions, that it has gained universal and all but exclusive preference. No one now thinks of attacking this delicate problem by the comparatively clumsy mode of determining absolute right ascensions and declinations at intervals of six months, and trying to distil, from a confused mass of minute errors, the subsensible evidence of those periodical changes which reflect across the gulf of sidereal space the movement of the earth in its orbit.

Nevertheless, the first genuinely measured stellar parallax was so far a casual result that it was arrived at in the ordinary course of observation. It presented itself, as it were, unsolicited. Alpha Centauri combines Struve's three criteria of vicinity. It is exceedingly bright; it has a large proper motion; and its components revolve swiftly in a wide orbit. No other star in the sky seemed beforehand so likely to come within the grasp of terrestrial determinations; and none has yet proved to be so little remote. Henderson's observations of it, made at the Cape in 1832-33, were discussed with a view to sifting out from them a parallactic element, after he had learned that the star's rapid onward movement afforded a presumption of relative nearness to the earth. Nor were his expectations belied. A parallax of about one second manifestly implied by annual changes of declination, was partially confirmed by observations of the same object in right ascension made by Henderson's assistant, Lieutenant Meadows.

His announcement to this effect, January 3, 1839,[1] was received with doubts, justifiable, perhaps, considering the numerous precedents for illusion on the point, but not justified by the upshot. Bessel's similar (and slightly prior) communication regarding 61 Cygni, inspired, on the other hand, general confidence. The Königsberg series, indeed, though by no means fortified with all the precautions now

[1] *Memoirs R. Astr. Soc.* vols. xi. p. 61; xii. p. 329.

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deemed necessary, seemed beautifully complete. The observations were of the differential kind, and the harmonious flow of the curves into which they were projected by Mr. Main,[1] prompted the conviction that here at last was a stellar parallax, the genuineness of which was beyond cavil. The extreme importance of its detection, pronounced by Sir John Herschel the greatest triumph ever achieved by practical astronomy, can be estimated from Bessel's declaration that, until it was actually compassed, he was unable to form an opinion as to whether the parallaxes of the nearest stars should be reckoned by tenths, or by thousandths of a second![2]

The distance from the earth of 61 Cygni has been more frequently investigated than that of any other star, and some trifling discrepancies notwithstanding, may be considered as satisfactorily ascertained. Bessel's parallax of about a third of a second was augmented to $0''{\cdot}42$ by Auwers's rediscussion in 1868 of the same data, and to $0''{\cdot}47$ by Sir Robert Ball's measures at Dunsink.[3] Dr. Hermann Davis's discussion of the Rutherfurd plates in 1898 yielded a value of $0''{\cdot}36$;[4] Professor Barnard's observations in 1900-2 with the Yerkes refractor proved closely confirmatory.[5] This unobtrusive star-pair may then be confidently located at a distance of nine light-years from the earth.[6]

We accordingly see the coupled stars, not where they *are*, but where they *were* nine years ago; that is (since their proper motion is about $5''{\cdot}12$ yearly) just forty-six seconds of arc behind their true places. The effulgent points terrestrially determined are then mere simulacra of the real stars; they pursue, without ever overtaking them; they would continue to shine and to travel for nine years after their originals had been blotted out of the visible creation. Our views of all moving objects are of course to some extent affected by this curious kind of light-aberration; but in the sidereal heavens it attains proportions that are not only large, but, for the most part, incalculably large. Our survey of the background of

[1] *Memoirs R. Astr. Soc.* vol. xii. p. 42.
[2] *Astr. Nach.* No. 385.
[3] *Abhandlungen Kön. Akad.* Berlin, 1868, p. 114.
[4] *Columbia University Contributions*, No. 13, p. 125.
[5] *Report Yerkes Observatory*, 1879-1902, p. 13.
[6] Barrett, *Astroph. Journ.* vol. xviii. p. 398.

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the sky may lag centuries, even millenniums, behind our simultaneous survey of its foreground; and the disturbed synchronous relations between the varied luminous contents of the sphere are, to our perception, incapable of readjustment.

Transported to the place of 61 Cygni, our sun would appear about eighteen times brighter. It would represent a star not of the fifth, but of the second magnitude, such as Polaris, or one of the Pointers. Nor is it likely that the Swan binary is massive much beyond the proportion of its luminosity. The extreme slowness of its revolutions, on the contrary, intimates a comparatively slight power of mutual attraction.

Fraunhofer's construction of the instrument with which Bessel observed 61 Cygni, marked the turning-point from failure to success in parallactic inquiries. The heliometer is specially adapted to facilitate them. It has two chief points of superiority over the ordinary equatoreal and micrometer. In the first place, much wider pairs of stars can be grasped with it, its compass being, by the mobility of the semi-lenses, extended far beyond the limits of a single field of view. The selection of comparison-stars is thus greatly enlarged, and the chances of a systemic connection with the central star fatal to the purpose of the designed operation, are reduced to a minimum. In the next place, the stars under observation can be visually equalised by placing a wire-gauze screen of any desirable opacity over the segment of the object-glass forming the image of the brighter one, whereby baffling personal errors are completely eliminated. These are the chief, but not the only features of the heliometer tending to promote critical precision; and not the least among Sir David Gill's services to astronomy was his development of the powers and applications of this unique instrument.

Bessel's success with 61 Cygni gave the impulse to numerous undertakings of the same kind. Their result depended mainly on the skill or luck of the observers in picking out from innumerable indefinitely remote stars the few near enough to be sensibly displaced through the effects of the earth's motion. Two circumstances mainly determined their choice.

That distance is a factor of stellar brightness is so obvious

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a truth that it may almost be reckoned a truism. Admitting the widest possible range of variety in actual light-power, the likelihood still remains that the most lustrous objects will be found among those in closest proximity to the earth. Exceptions, it is true, abound; but, on a wide average, the theoretical inverse ratio between distance and the square root of total light furnishes at least a valuable guide to actual fact.[1]

Several conspicuous stars — Vega, Arcturus, Capella, α Cygni, and Polaris—were, on this ground, fixed upon for investigation by C. A. F. Peters in 1842-43.[2] His results, obtained with the Pulkowa vertical circle, were absolute, being irrespective of comparisons with other stars; but the deduced parallaxes were so small, and their "probable errors" so relatively large, that it was difficult to place much confidence in them. Yet they came surprisingly near the truth.

A second criterion of nearness was found in the appearance of rapid motion. This varies in the same proportion as distance, but in the reverse sense. At twice the distance, an identical velocity produces only half the angular displacement; at three times the distance, one-third, and so on. Thus, apparent swiftness, no less than apparent lustre, depends in part upon vicinity, and the largest proper motions must belong, on the whole, to the nearest stars.

And, on the whole, parallax-hunters taking rapidity of advance for their guide have prospered the best. A 7·5 magnitude star in Ursa Major, flitting annually over $4\frac{3}{4}$ seconds of angular space, was found by Winnecke in 1858[3] to have a parallax ($= 0''{\cdot}46$) inferior only, among those as yet determined, to that of α Centauri. This insignificant object, numbered 21,185 in Lalande's great catalogue, is separated from the earth by a light-journey of seven years, and to that extent our observations of it are retarded. So that it is in reality always $33''$ in advance of the place we are compelled to assign to it. For a body claiming the rank of a sun, it is either very small or very obscure. Our own ruling orb is 260 times more luminous.

[1] Struve, *Mens. Microm.* p. clxii.

[2] *Zeitschrift für pop. Mitth.* Bd. iii. p. 104; *Mémoires*, St. Pétersbourg, t. vii. p. 140, 1853; *Astr. Nach.* No. 1147.

[3] *Astr. Nach.* No. 1147.

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An 8·5 magnitude star in the same constellation (Lalande 21,258), also distinguished for apparent velocity, disclosed to Auwers's measurements with the Königsberg heliometer in 1860-62 a parallax of 0″·26,[1] corresponding to a light-journey of 12½ years, and a permanent displacement on the sphere, due to its proper motion in that interval, of 55″. The real brilliancy of the star is only $\frac{1}{200}$ that of the sun. A still smaller star in Draco (Oeltzen 17,415) gave an even more emphatic warrant to confidence in swiftness, rather than in lustre, as a certificate of proximity. Krüger, induced by its yearly movement of 1″·27 to subject it to experiment, obtained a parallax of one quarter of a second;[2] while the fine binary system, 70 Ophiuchi, with an annual motion of 1″·13, proved to be removed from the earth by twenty years of light travel (parallax 0″·16).[3] And all these results seemed, from the smallness of their "probable errors," to be exceedingly trustworthy.

The probable error of any result, however, represents only what we may call the *uncaused* inaccuracies of the observations upon which it is founded. It sums up, according to the doctrine of probabilities, the effect of their deviations, in either direction, from the mean. But it takes no heed of "systematic" errors due to causes working steadily in one sense, but, so to speak, underground. These are the real sources of mischief from which fallacious parallaxes have abundantly sprung in times past, and which cannot, in the present and future, be too carefully guarded against. Especially formidable are certain slight idiosyncrasies of perception, by which measures of distance become modified with the varying positions of the line of direction between the objects measured, relative either to the vertical or to the line joining the observer's eyes. And since this subtle spring of error rises and falls harmoniously in a period of a year (because dependent upon the uranographical situation of the stars under scrutiny), it would be capable not only of completely vitiating observations apparently accordant, but even of simulating parallactic changes that had no real existence. Instrumental errors, too,

[1] *Monthly Notices*, vol. xxiii. p. 74.
[2] *Acta Societat. Scient. Fennicæ*, t. vii. p. 383.
[3] Krüger, *Astr. Nach.* Nos. 1210-12.

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connected with changes of temperature, or the deforming power of gravity (as conditioned by the shifted positions of the telescope at different seasons) take the same cyclical course; and there can be no doubt that to some such lurking deceptive influence the parallax of $0''{\cdot}07$ attributed to *a* Herculis by Captain Jacob in 1858,[1] owed its origin. Since the star chosen for comparison was no other than the well-known physical attendant of the object examined, the fact of illusion is patent.

The exigencies of this kind of work were recognised and fully explained in an elaborate paper published by Dr. Döllen of St. Petersburg in 1855;[2] and his principles were ably carried into effect by Dr. Brünnow in a series of investigations of stellar parallax at Dublin between 1868 and 1874. The example thus set of the thorough elimination of errors, at once personal and periodical, has since been generally followed. More effectually than by most other men, the famous "Know thyself" of the old Greek philosophers has been taken to heart by astronomers. Their anxious and elaborate inquiries regard not merely microscopic inequalities of scale-divisions and screw-values, changes in refraction, corrections for aberration and proper motion, but the cunning tricks of their own nerves, the caprices of cerebration, all the varying conditions of perception in the organism at their individual command.

None of these precautions were neglected in the important work executed by Gill and Elkin at the Cape in 1881-83.[3] Fully alive to its subtle requirements, they gave to their determinations a precision entitling them to standard rank. Sir David Gill's discussion, especially, of the parallax of *a* Centauri is a model inquiry. It leaves, one may say, no stone unturned beneath which a source of illusion might lie concealed. The resulting parallax of $0''{\cdot}75$, accordingly, obtained by independent comparisons with no less than four pairs of adjacent stars, is probably more nearly accurate than any value of the sort yet registered. The fact is definitely assured that light, which flies from the sun hither in eight minutes,

[1] *Madras Observations*, 1848-52, Appendix; *Memoirs R. Astr. Soc.* vol. xxvii. p. 44.

[2] *Bulletin de l'Acad.* St. Pétersbourg, t. xiii. Suppl.

[3] *Memoirs R. Astr. Soc.* vol. xlviii.

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spends four years and four months on the journey from our nearest known neighbour among the stars. The corresponding distance is, in round numbers, twenty-five billion miles.

A joint attack on Sirius disclosed a parallax of 0″·38, implying a light-journey of 8·6 years. These were the first measures of the dog-star made under perfectly suitable conditions, and their repetition by Sir David Gill in 1888-89 with the 7-inch Cape heliometer, finally established their accuracy.[1]

Of the nine southern stars investigated by Gill and Elkin, five—ϵ Indi, o_2 and e Eridani, Lacaille 9342, and ζ Toucani—were chosen for their large proper motions, and all proved to be measurably near the earth.[2] Canopus and β Centauri, on the other hand, included in the list because of their distinguished brilliancy, averred their extreme remoteness. From the former in particular, no symptom of displacement, progressive or periodical, could be elicited then or subsequently. This is really, when we come to consider it, an astonishing result.

Second only to Sirius in the southern hemisphere, the star of the Nile far outshines every star north of the celestial equator. As chief of the great constellation Argo, it seems to command, while standing slightly aloof from, the dazzling array of all stellar ranks spanning the heavens from the Greater Dog to the Cross. And since its spectrum is marked by nearly the same kind and amount of absorption as that of Procyon, we cannot safely conclude its mass to be abnormally small in proportion to its light.

Both, regarded absolutely, must be enormous. The failure of persistent efforts to detect any parallactic shifting in Canopus obliges us to suppose it so far off that its light needs *at least* 300 years to reach us; how much longer, it is impossible to tell. At this minimum distance, our sun would shrink to a tenth-magnitude star; it would be one of the dense shoal of telescopic objects imperceptible to unaided sense, and scarcely yet individualised by the industry of astronomers. But 22,000 stars of tenth magnitude give only the light of one Canopus; whence it follows that Canopus

[1] *Annals of the Cape Observatory*, vol. viii. pt. ii. p. 24.
[2] See Appendix, Table V.

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is certainly brighter, and may be very greatly brighter, than 22,000 suns like ours. This conclusion is startling, but appears inevitable. Four reference-stars, widely separated, are unanimous in its support.

Beta Centauri, one of the so-called southern Pointers, takes rank as of average first magnitude. Sir David Gill's final result assigned to it a parallax of $0''{\cdot}03$, equivalent to a light-journey of 109 years. Our sun, accordingly, shines with no more than $\frac{1}{400}$ the lustre of this white orb.

The time had now come when a change in the system upon which inquiries of this kind were prosecuted seemed feasible. Hitherto, observers had been content to select the most promising subjects for their experiments without any regard to the co-ordination of results. The outcome was a collection of detached statements as to stellar distances, interesting, each by itself, in a high degree, yet incapable of being combined for the purpose of any general conclusion. So long ago as 1853, Dr. Peters had pointed out that what was needed for obtaining a fundamental acquaintance with the structure of the sidereal world was not so much the determination of exceptional parallaxes, as the steady compilation of data for some well-grounded inference relative to the distances of defined star-classes.[1] But it was not until thirty years later that it became possible to act on the suggestion.

Encouraged by the success of the work just accomplished, Sir David Gill proposed, January 11, 1884, a scheme of attack upon the problem of star-distances in its widest bearings. Two "great cosmical questions" presented themselves to him as answerable by the judicious distribution of some years' continuous labour. The first related to the average parallaxes of stars belonging to successive orders of brightness; the second to the connection between parallax and proper motion.[2]

A plan was accordingly concerted by which Dr. Elkin undertook the measurement, with the new Yale College heliometer, of a considerable number of representative northern stars, while Sir David Gill dealt with a corresponding southern list at the Cape. Its final outcome was the authentic

[1] *Mémoires de St. Pétersbourg*, t. vii. p. 149.
[2] *Memoirs R. Astr. Soc.* vol. xlviii. p. 191.

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determination of thirty-two parallaxes—ten in the northern, twenty-two in the southern hemisphere, including those of all stars of the first magnitude.[1] And thus at last, a scale-unit for the stellar universe was provided. For, once we know the distance in billions of miles or light years corresponding to the first magnitude—the distance, that is, at which a "mean star" would shine with about the lustre of Spica or Regulus—the distances corresponding severally to the lower magnitudes follow as a matter of course. They are linked together (unless we are deceived by systematic changes of brightness) by an invariable proportion. We have already explained what is meant by the "light-ratio,"[2] but it may here be repeated that a star of any given magnitude is, by definition, one 2·512 times brighter than a star of the magnitude next below, and 2·512 times less bright than a star of the magnitude next above it. But, since light varies inversely as the square of the distance, any star removed to $\sqrt{2{\cdot}512} = 1{\cdot}585$ times its actual distance, would show exactly one magnitude fainter than it did before. This number, then, 1·585, the square-root of the light-ratio, may be designated the "distance-ratio." It represents the difference of distance equivalent to a difference in light of one stellar magnitude. The *relative* mean distances of the various classes of stars are then known; to render them *absolute*, we only need to ascertain the real mean distance of any of those classes.

It is true that, within each class, vast disparities exist. Small stars, comparatively near the earth, take their stand on the same level of apparent brightness with indefinitely large, but indefinitely remote bodies. What is invariable for each magnitude is the *proportion* between real brilliancy and the square of the distance. Symbolically expressed, $\frac{l}{d^2}$ is constant. That is to say, photometric uniformity results from a certain balance being struck between remoteness and light-power, by which the effect of equality is produced. The law, however, connecting average distance with apparent lustre is not invalidated even by the limitless variety included

[1] *Annals Cape Observatory*, vol. viii. pt. ii. 1900; *Publications Yale Observatory*, vol. i. pt. vi. 1902.

[2] See *ante*, p. 19.

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in the above expression. The extremes are vastly wide apart, but the mean remains practically the same. It should, nevertheless, be clearly borne in mind that the conclusions thus obtained are general, and should only be generally applied. Referred to particular cases, they may be fallacious and misleading. Nor are we assured that the stars are scattered indifferently as regards their real lustre. An average star in one region of space might conceivably be larger or smaller, dimmer or brighter, than an average star elsewhere. If this were so, the theoretical distance-ratio would fail as a guide to investigation. And it is remarkable that the mean distances of photometric classes of stars derived from their proper motions show a lower rate of increase with faintness than they should if a uniform arrangement prevailed.[1] A further *caveat* relates to the distribution of stellar spectra. If the manner of their assortment depends upon remoteness from our system, the geometrical interpretation of photometric data should be modified. This it assuredly does to some extent, although it seems to be more essentially conditioned by the lines of sidereal structure. The ratio of brightness to distance is probably not identical within the galactic zone and outside of it.

Meanwhile, the Cape and Yale results give $\frac{1}{10}$ of a second of arc as the average parallax of first-magnitude stars in all parts of the sky. They establish, at a distance of thirty-three light years, the first halting-stage for explorations of sidereal space. Thus inconceivably remote, taken all round, are the brightest of the stellar host. Our sun, so placed, would sink nearly to the fifth magnitude. Its fellow suns, then, far surpass its glory.

On the scale determined at Yale College, the mean distance of stars of the second magnitude is fifty-two light years (parallax $0''{\cdot}063$); stars of the third magnitude are at eighty-two light years (parallax $0''{\cdot}04$), and so on; the invariable ratio of 1·585 regulating the increase of distance and decrease of magnitude for each descent of one step, provided only that light suffers no ethereal absorption. When we get down to the sixteenth magnitude, which is about the *minimum visibile*

[1] Newcomb, *The Stars*, p. 313, where (as Mr. T. E. Heath has remarked) a value of 1·414 for the distance-ratio is implied.

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in the largest telescopes (the Yerkes refractor attains to one magnitude lower still), we find the theoretical light-interval lengthened to 33,000 years; but there is no certainty that any such far-travelled rays reach us. The regular progression of distances may not extend so far. It must stop somewhere, if the stellar system be—as we have reason to think it is—of finite dimensions; at what particular magnitude the break occurs, it would at present be futile to conjecture. All that can be said is that, distance becoming at length eliminated as a factor of magnitude, the differences of the faintest stars represent, chiefly or solely, real inequalities in shining. There may possibly, for instance, be no "mean distance" corresponding to the sixteenth magnitude. The stars of that rank would not then, on the whole, be further off than those of the rank next above them, but would, on the whole, possess only $\frac{1}{\text{fifth}}$ of their real light. This *must* be the case—so far as we can see—at some stage of the descent into the abysses around us.

Besides Canopus, four among the twenty-one brightest stars in the sky were found by Gill and Elkin inaccessible to parallactic research. These are Rigel, Spica, α Cygni, and β Crucis. All five must be Brobdingnagian orbs; their magnificence defies the realising efforts of imagination. In singular contrast to them are certain swift, but dim stars measured by Sir David Gill, notably one in Pictor of 8·5 magnitude, which cannot, since it has a comparatively large parallax, shine with more than $\frac{1}{300}$ the lustre of our modest sun. Ten, in fact, of the twenty-two stars determined at the Cape, proved to fall short, in sundry degrees, of the solar standard of light-power.[1] But to what extent they depart from the wide average of the sidereal system, we have at present no means of judging. All that can be said is that the variety embraced by it has a prodigious scope.[2]

Of the ten stars measured at Yale, Procyon, with a parallax of 0″·334, giving a light-journey of 9·8 years, was found to be the nearest to the earth. Altair, at a distance of 14 light-years (parallax 0″·232), came next; Aldebaran, at 30 light-years (parallax 0″·109), third. From Arcturus and Betelgeux

[1] *Cape Annals*, vol. viii. pt. ii. p. 141.

[2] Gill, *Proc. S. African Phil. Society*, Sept. 17, 1902.

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an almost identical result was derived. Each is plunged in a profundity of space represented by 126 years of light-travel; and this implies the real luminosity of Arcturus to be approximately 1000, that of Betelgeux to vary a little on either side of 800 times the solar brightness.

So closely and so consequentially have advances in this arduous branch followed the growth of improvement in heliometers, that direct visual measurements for the purpose with any other instrument might almost seem waste of labour. Nevertheless, the transit-circle has been unexpectedly rendered thus available. Professor Kapteyn originated, in 1889, the determination of stellar parallaxes by differences in right ascension, giving for fifteen stars results at once acknowledged as authentic;[1] and his method was applied to ninety-six stars by Professor Flint at the Washburn Observatory (U.S.A.) in 1893-96.[2] It is safe and expeditious, and serves as a useful adjunct to work with the camera. Photographic parallax researches were effectively set on foot by Professor Pritchard. His first experiment was with the classic 61 Cygni, of which 330 separate impressions, obtained in 1886-87, furnished the materials for 30,000 measures, or "bisections" of star-images.[3] For the immediate end in view, these extraordinary pains were largely superfluous; but they had the ulterior object, fully attained by their means, of establishing the credit of a novel and unfamiliar method. The most delicate of all astronomical inquiries was thenceforward, with the full assent of experienced judges, admitted to be within the competence of the celestial photographer.

The advantages of determining parallaxes from sensitive plates are manifold. Perhaps the chief of them is the nearly indefinite power of control they afford. Any of the imprinted stars, situated at all near the prolongation of the major axis of the parallactic ellipse (in other words, with a tolerably large "parallax-factor") may be used as a point of reference. Comparisons can thus be multiplied almost at pleasure, and inferred displacements with regard to one star checked by recourse to another, duplicate plates being at hand for addi-

[1] *Astr. Nach.* No. 2935; *Annalen der Sternwarte in Leiden*, Bd. vii.
[2] *Publ. Washburn Observatory*, vol. xi. 1902.
[3] *Monthly Notices*, vol. xlvii. p. 87.

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tional safety. By the proper use of such safeguards, delusive results can be all but certainly excluded. Moreover, *relative* parallax becomes virtually *absolute* when comparisons are made with a great number of stars, most of which are presumably too remote to complicate the result by perspective movements of their own.

Within its peculiar province photography comprises stars too faint to be conveniently dealt with by visual means. For the images of those much brighter, over-exposed through the necessity of giving the small stars in their neighbourhood time to imprint themselves, become diffused into blurred discs unfit for accurate bisection. Plates, on the other hand, taken by Dr. Schlesinger with the Yerkes refractor in 1903-4 proved well adapted for obtaining the parallaxes of eighth and ninth magnitude stars.[1] Trial was made of only three; but one of them was a double star in Cepheus, found to be ten times nearer the earth than Vega or Arcturus (parallax = $0''{\cdot}278$). Yet the pair give no more than $\frac{1}{380}$ the sun's light, though their rapid mutual revolution suggests the presence in the system of considerable attractive power. It will be curious to ascertain, when their orbit develops sufficiently to be computed, the relation in its members of mass to luminosity.

The main object of present inquiry is to obtain a wider basis for general conclusions regarding the distances of the stars. For this purpose it is more important to secure a considerable number of parallaxes reasonably well determined than a few reduced by scrupulous care within the narrowest possible bounds of error. Research in this sense is already well on its way. From statistics of proper motion, Professor Kapteyn has derived trustworthy estimates of the mean distances of the stars according to their photometric rank.[2] In doing so he found it advisable to distinguish between the members of different spectral classes, since the fact clearly emerged from his discussion that—as Mr. Monck had indicated several years previously[3]—Sirian and helium stars are fully twice as remote, on an average, as solar stars of the same magnitude. A colossal scheme of direct inquiry was besides

[1] *Astroph. Journ.* vol. xx. p. 123.
[2] *Astr. Nach.* No. 3487; *Groningen Astr. Publ.* No. 8.
[3] *Astr. and Astrophysics*, vol. xi. p. 701.

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sketched by the Groningen astronomer in 1889,[1] and its feasibility established by experimental measurements of plates taken by Professor Donner at Helsingfors, the results of which were made public in 1900.[2] But the proposed photographic survey of the heavens, by which the parallaxes of 800,000 stars might possibly become known, is still in abeyance. Its execution would be most costly in time, labour, and money; and their lavish outlay is discouraged by the baffling smallness of the quantities sought to be disclosed.

Meanwhile we may attempt to summarise the outcome of preliminary explorations. It is, in the first place, decidedly unfavourable to the existence of any large parallaxes. The possibility is, of course, by no means excluded that stars may be found much nearer to the solar system than α Centauri, but their discovery is growing every year less and less probable. Sir Robert Ball[3] examined some years ago about 450 objects in a manner which, though summary, would have sufficed to bring to view any parallax of a single second of arc. None was forthcoming. His list comprised a number of red and variable stars, Nova Cygni, Webb's planetary nebula, and the Wolf-Rayet gaseous stars in Cygnus; and it may be noted in passing that spectral peculiarities are almost invariably associated with an uncommon degree of immobility in the sky. The ninety-six stars reviewed by Professor Flint on Kapteyn's method were of a more promising character; and ninety-two were selected by Dr. Chase for rapid scrutiny with the Yale heliometer, because their large proper motions supplied an argument of proximity; yet, among them all, not one seems to be within a five years' light-journey of the earth. Indeed, parallaxes even of one-tenth of a second, signifying a light-interval of thirty-three years, are held by Professor Kapteyn to be extremely scarce.[4] On the whole, perhaps one hundred stars[5] have been shown to swing to and fro sensibly in response to the earth's orbital vibration; and the number of fairly well determined parallaxes may be put at about seventy.[6]

[1] *Bull. de la Carte du Ciel*, No. 1, p. 262. Cf. Pulfrich, *Astr. Nach.* No. 4013.

[2] *Groningen Astr. Publ.* No. 1.

[3] *Dunsink Observations*, vol. v.

[4] *Groningen Publ.* No. 1, p. 93.

[5] Newcomb, *The Stars*, p. 149.

[6] See Appendix, Table V.

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The cardinal truth emerging from these inquiries is that of the extreme isolation of the solar system. A skiff in the midst of a vast unfurrowed ocean is not more utterly alone. About the same proportion would be borne by an oasis one mile across to a desert twenty times as extensive as the Sahara, that our sun with his entire planetary household bears to the encompassing void of space. The enormity of its blank extent is strikingly illustrated by Father Secchi's remark that the period of a comet reaching at aphelion the middle point between our sun and the nearest fixed star, would be of one hundred million years;[1] and, by recent measures, the nearest fixed star has been pushed further back into space by one-quarter the distance assigned to it when he wrote. Yet the sun is no isolated body. To each individual of the unnumbered stars strewing the firmament, down to the faintest speck of light just shimmering in the field of the Lick refractor, it stands in some kind of relationship. Together they master its destiny and control its movements. Independent only so far as its domestic affairs are concerned, it is bound, as a star to the other stars, by influences reaching efficaciously across the unimaginable void which separates it from them. The outcome of those influences in the translatory motion of the solar system we shall consider in the next chapter.

[1] *Les Étoiles*, t. ii. p. 146.

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CHAPTER XXIII

TRANSLATION OF THE SOLAR SYSTEM

THE study of the stars inevitably leads us to consider the advancing movement in the midst of them of the sun and its attendant train of planets. There can be no reasonable doubt —and the thought is an astounding one—that we are engaged on a voyage through space without starting-point or goal that we can know of, which may prove not wholly uneventful. Its progress may possibly bring about, as millenniums go by, changes powerfully influential upon human destinies; nay, an incident in its course may at any time, by the inscrutable decree of Providence, terminate the terrestrial existence of our race, and consign the records of its civilisation in dust and cinders to the arid bosom of a dead planet. A curious sense of helplessness, tempered, however, by a higher trust, is produced as we thus vividly realise how completely we are at the mercy of unknown forces—how irresistibly our little "lodge in the vast wilderness" of the universe is swept onward over an annual stretch of some four hundred millions of miles, under the mysterious sway of bodies reduced by their almost infinite distances to evanescent dimensions.

But, as things are constituted, the translation of the sun's household is a necessity, albeit one of startling import to ourselves. The stellar system is maintained by the balance of forces, and motion is the correlative of force. As a star among stars, the sun can only maintain a separate existence by contributing its share to those harmonies of movement by which "the heavens show forth the glory of God." Destruction would be the eventual penalty of even a moment's immobility —a penalty, indeed, which might not be exacted until after the

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lapse of many millions of years. It may reasonably be assumed that *a* Centauri exercises upon the sun the strongest attraction of any individual star; but a collision would ensue very tardily upon abandonment to its influence. The sun (if undisturbed by competing pulls) would fall from a position of rest towards its next neighbour, less than the third of an inch in the first month; the second month would see despatched nearly a full inch of the journey of twenty-five billions of miles; and although the acceleration would of course grow more rapid as the distance diminished, upwards of fourteen million years should pass before the fires of sun and star, probably become extinct during their gradual approach, could be rekindled by the catastrophe of their impact.

There is then an *à priori* certainty that the sun moves; and assurance on the point is rendered doubly sure by inferences from observed facts. For besides their annual parallax due to the earth's motion round the sun, the stars have a "secular" or "systematic" parallax depending upon and attesting the reality of the sun's motion round an unknown centre. Let us see how this systematic parallax can be investigated.

If the sun alone were in motion, and the stars at rest, the results in perspective displacements would be simple and unmistakable. Each star would appear to travel backward along a great circle of the sphere, passing through the two points towards and from which the sun's course was directed. So that there would be the semblance of a general retreat from the "apex" or solar *point de mire*, coupled with a thronging-in from all sides towards the opposite point, or "anti-apex." For each particular star, the amount of displacement should vary, inversely as its distance from ourselves in space, directly as the sine of its angular distance from the apex. Hence, if the annual parallax of even one such sensibly shifting star were determined, not only the rate, in miles per second, of the solar progression would at once follow, but the parallax of every other sensibly shifting star in the heavens could be deduced by a simple calculation from the relative quantity of its apparent movement.

But the stars are not at rest. They have movements of their own, greatly swifter, in many cases, than that of the sun.

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Perspective effects are thus to a great extent masked. Yet they subsist. It is mathematically certain that every star, whatever its own course or speed, reflects the sun's motion in the strict measure of its position with regard to it. What are called the "proper motions" of the stars are then made up of two parts, one real, the other apparent. They include a common element, the separation of which from the heterogeneous admixtures disguising it, constitutes the problem to be solved.

With the instinctive appreciation of genius, Herschel went straight to the heart of the matter. What had to be done, he saw clearly, was to find out the direction which should be given to the sun's course, in order to make it account for as large a proportion as possible of the sum-total of stellar movements. "Our aim must be," he wrote in 1805, "to reduce the proper motions of the stars to their lowest quantities."[1] And again: "The apex of the solar motion ought to be so fixed as to be equally favourable to every star." But how is this to be done? Very simply, if we only consider, as Herschel did, a few of the brightest stars.

Take, for example, four stars with conspicuous movements, two in the northern, two in the southern hemisphere; namely, Vega, Capella, Sirius, and Fomalhaut. The great circles, of which each annually describes a minute arc, traced backward on the sphere, very nearly intersect in a single point situated in the constellation Hercules.[2] Had we only the motions of those four stars to consider, we should accordingly infer without hesitation the "sun's way" to lie thitherward. Nor should we be very far wrong. The most refined modern determinations of the solar apex, founded upon the motions of several thousand stars, differ among themselves to an extent comparable with their mean deviation from the result of the extremely summary proceeding just indicated.

The graphical method, however, is evidently applicable only to a very restricted stock of data. When a crowd of stars have to be taken into account, the points of intersection of their respective circles of motion become spread over too wide an area for a "mean apex" to be struck out fairly

[1] *Phil. Trans.* vol. xcv. p. 248.

[2] This was remarked by Klinkerfues, *Göttingische Nachrichten*, 1873, p. 350.

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between them, even by the exercise of a judgment as discriminating as that which in 1783 led Herschel to place the goal of solar travel in the vicinity of λ Herculis. The accumulated facts must then be dealt with by a method at once stricter and more comprehensive. A glance at the nature of the task in hand easily suggests to a mathematician what that method should be.

The proper motions of the stars give, as already hinted, the plainest evidence of individuality. The lines pursued by them run in all possible directions. But a sub-stratum of regularity underlies this seeming confusion. A mere inspection of the signs *plus* and *minus*, signifying respectively east and west, and north and south, attached in catalogues to the components in right ascension and declination of stellar movement, suffices to show a general prevalence of law through the unequivocal tendency of the signs to vary concordantly in passing from any one to an adjacent region of the heavens.[1] At a *coup d'œil*, Argelander fixed the point from which this under-current of motion flowed, and so gave an improved apex for the course of the sun, confirmed in the main by subsequent research.[2] It is then clear, in the first place, that no movement possibly assignable to the sun can explain all stellar displacements; a large residuum being real, and therefore by no ingenuity to be got rid of. While in the second place, the nearer the truth is approached as regards the direction and amount of the sun's motion, the smaller obviously this residuum will be. In other words, the most probable value of the solar motion will be that which renders the "sum of the squares of the residuals" of stellar motion a minimum.

But why the sum of the squares, and not the simple arithmetical sum of the outstanding proper movements? It needs only common sense, aided by the most elementary geometry, to get a sufficient insight into the reason. Any one can see, with the help of a pencil and a piece of paper, that, if a line be divided into two segments, and squares be constructed on the segments, the sum of those squares will be the least possible when the line is equally divided, and will increase continually with the inequality of the segments. This simple fact gives

[1] Stone, *Monthly Notices*, vol. xxvii. p. 239.

[2] *Mémoires présentés à l'Acad.* St. Pétersbourg, t. iii. p. 569.

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the clue to the principle of "least squares." Its object is to elicit such a quantity as will make the outstanding errors of observation, or any other kind of residuals, as small as possible *all round*. Not merely small taken in the aggregate, but reduced impartially to a uniform level of insignificance. Under these circumstances, as we have seen from the consideration of our divided line, the sum of their squares will be a minimum; and it can be mathematically demonstrated that the most probable result of such investigations as are susceptible of this kind of treatment, is arrived at when the condition of "least squares" is fulfilled.

This mode of attack upon the problem of the sun's translation was first employed by Argelander in 1837. Assuming provisionally the correctness of Herschel's apex, he proceeded to compute for each of 390 stars with ascertained proper motions the lines along which those motions should proceed if due to systematic parallax alone. Their deviations from the prescribed directions gave him "angles of error," which, placed in the category of casual errors of observation, and treated by the method of least squares, indicated a corrected apex, such that by its adoption, the sum of the squares of the differences between what was calculated and what was observed—that is, between the purely parallactic drift of the stars and their actual displacements—was reduced to the least possible amount. The solar movement was, in a word, so fixed as, in Herschel's phrase, "to be equally favourable to every star," a condition fulfilled by directing it towards a point in right ascension 260° 51′, north declination 31° 17′.[1] But there is much reason to believe that the position of maximum neutralisation—so to call it—really lies some fifteen degrees further to the east.

An important modification of his method was introduced by Sir George Airy in 1859.[2] Abolishing the conception of a spherical surface of reference, he defined the linear movements in space of the sun and stars with regard to three directions at right angles to each other ("rectangular coordinates"). No assumption of any kind was then needed; the subject was treated with the utmost strictness and gener-

[1] *Mémoires présentés*, t. iii. p. 590.
[2] *Memoirs R. Astr. Soc.* vol. xxviii. p. 143.

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ality, and some possible causes of error were removed. Airy's had many points of theoretical superiority over Argelander's method. That, however, of introducing the consideration of the *quantity* of each star's movement was to a great extent counterbalanced by the necessity which it involved of adopting precarious suppositions as to the distances of the classes of stars employed. The apex for the solar movement resulting from the consideration of 113 stars was situated in R.A. 261° 29′, Dec. + 24° 44′; while Mr. Main's similar treatment of 1165 stars shifted it to R.A. 263° 44′, Dec. + 25°.[1]

This great subject was again investigated by M. Ludwig Struve in 1887.[2] The incitement to undertake a task rendered formidable by the very wealth of the materials at his disposal, was afforded by Auwers's fresh reduction of Bradley's Greenwich observations. From a comparison of the star-places authoritatively determined for 1755, with those given in the St. Petersburg catalogue for 1855, a list of 2814 proper motions was derived, of which 2509 were available for M. Struve's purpose. Among the stars for various reasons excluded, were the seven swiftest travellers, as unduly affecting the result through motions no doubt mainly original.

The outcome of this exhaustive discussion was to place the apex of the solar motion in R.A. 273° 21′, north declination 27° 19′, a rate being assigned to it such that the space traversed in a century, viewed square from the average distance of a sixth-magnitude star, would subtend an angle of 4″·36. Admitting that stellar distance varies inversely as the square root of stellar brightness, hence that stars of the first are, on an average, only one-tenth as remote as stars of the sixth magnitude, we can, with the help of Dr. Elkin's mean parallax for the former class, translate this angular into linear velocity. It comes out 14½ miles a second.

Well-nigh the whole of the stars visible to the naked eye in the northern hemisphere concurred in M. Struve's determination. It was conducted on Airy's method, likewise adopted in 1890 by Lewis Boss in a discussion of 253 proper motions extracted from the "Albany zone," the observation of

[1] *Memoirs R. Astr. Soc.* vol. xxxii. p. 27.

[2] *Mémoires de St. Pétersbourg*, t. xxxv. No. 3, 1887.

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which had just then been completed for the Astronomische Gesellschaft Catalogue. He obtained an apex in R.A. 280°, D + 40°,[1] near the quadruple star ϵ Lyræ; and recurring to the subject in 1901, finally concluded for a point five degrees further north.[2] A notable attempt, too, was made by M. Oscar Stumpe in 1890[3] to show that the apexes separately deduced from various classes of stars shifted systematically on the sphere. This seemed to involve the important disclosure that the groups of stars considered had distinctive aggregate movements, and were hence dominated by different gravitational influences; but the effects brought to view have probably as much to do with the correction of catalogue-places as with the laws of sidereal construction.[4] That these are also concerned, was proved by a research based on the proper motions of Groombridge's circumpolar stars, executed by Messrs. Dyson and Thackeray at Greenwich in 1905.[5] Solving their equations separately for stars of the first and second spectral types, they obtained from the separate collections markedly divergent directions for the sun's route, and thus, as the upshot of their experiment, laid bare one of the hidden links between the dynamical and the physical relations of the stellar world.

A material advance was made towards disentangling the intricacies of the solar movement by an innovation in the treatment of proper motions. It might have been supposed that every device for their manipulation had been exhausted, and that the decipherment of their perspective significance was complete, at least in principle; yet Professor Kapteyn contrived, in 1893, to give it a novel stamp of clearness and certainty. Resolving one by one the whole stock of star-movements at his disposal along, and at right angles to, the great circle passing through a solar apex assumed as the most probable, he succeeded in isolating their parallactic element much more perfectly than had been done before. The fundamental nature of the problem was thus laid bare; obscurities were dissipated; and there ensued a determination of first-rate authority, according

[1] *Astr. Journ.* No. 213. [2] *Ibid.* No. 501.

[3] *Astr. Nach.* Nos. 2999-3000.

[4] Kapteyn, *ibid.* Nos. 3721-22, 3859-60; *Proc. Amsterdam Acad. of Sciences*, Jan. 27, 1900.

[5] *Monthly Notices*, vol. lxv. p. 428.

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to which the sun's path is directed towards a point in R.A. 274°, D + 30°, just six degrees south of κ Lyræ. Its substantial accuracy was vouched for by Professor Newcomb's masterly researches.[1] Profiting by long experience in evading pitfalls and estimating sources of error, he deduced from 2527 small proper motions a solar apex in R.A. 274°, D + 31°; from 600 larger, one situated in R.A. 277°, D + 31°. Which result deserves more confidence, cannot off-hand be decided; but we may hope—although this is by no means sure—that their difference represents the surviving extent of uncertainty.

The plan of inquiry just sketched, although it serves wonderfully well, on the whole, for the ascertainment of the route followed by the solar system in space, avails little for determining its velocity. For this purpose, the distances of the stars employed as indexes should be known; and they can only be estimated for ranks and classes, more or less precariously. Kapteyn and Newcomb have, however, vastly improved the method of evaluation, and they agree in fixing ten miles a second as the approximate rate of the sun's journey. But a more direct way of arriving at it has, in recent times, been thrown open.

We have elsewhere explained the principle of spectroscopic determinations of motion.[2] Their peculiar value consists in their independence alike of distance and of visible displacement. Referring to movements visually imperceptible, they complete knowledge of stellar velocities by giving their otherwise unknown "radial components." Apart from this marvellous application of the spectroscope, the real directions pursued by the stars as they travel could never have been ascertained, since we can immediately discern only that part of their motion lying *across* the line of sight, which, in individual cases, may be all or none. By the spectroscopic revelation, however, of motion *in* the line of sight, the missing element is supplied, precise and particular knowledge may be had for the asking, and the stars voyage under astronomical scrutiny, no longer as mere flitting bright specks on the surface of an imaginary sphere, but as suns in space of three dimensions, each with its secret *in petto*, and its destiny in reserve.

[1] *Astr. Journ.* No. 457, 1899; *The Stars*, p. 91.
[2] *Hist. of Astr.* 4th ed. pp. 200, 386; *ante*, p. 185.

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The effects of recession and approach on the light emitted by moving objects being physical and real, they remain unimpaired by distance. Out at the verge of the sidereal system, or close at hand within our own atmosphere, they are the same for the same velocities, and can, with a sufficient light-supply, be detected with equal facility. Hence their special applicability to the problem of the sun's speed. To determine it with very approximate accuracy, it needs only to compare the average radial celerity of a good number of stars lying in front of the sun's way with that of others he is leaving behind. Movements of approach must, on the whole, predominate in the one direction, movements of recession in the opposite, half the mean difference representing the rate of transport of our system relatively to the stars used for the comparison. The spectroscopic method, nevertheless, did not become really effective for this purpose until the twentieth century had begun to run its course. Experiments with the 51 stars radially measured at Potsdam were evidently tentative;[1] they forecasted rather than afforded results. At last, in 1901, Professor Campbell,[2] having collected with the Mills spectrograph data less inadequate to the end in view, deduced from them a movement of the solar system towards an apex in R.A. 277° 30,′ D + 20°, at the rate of 12½ miles a second. The velocity may be depended upon—it is unlikely to be erroneous by more than a mile per second; but the direction is subject to a somewhat wide uncertainty, especially as regards declination. For the 280 stars taken into account being situated for the most part in the northern hemisphere, the goal determined by their means was probably displaced towards the equator. The deficiency of southern stars will, however, be supplied by the work of the "Mills Expedition" now in progress at Santiago; and a research, based on symmetrically arranged materials, will then be practicable.

Thus, both the course and speed of the sun and planets are not only included in the category of things *knowable*, but there is every prospect of their becoming known with more and more satisfactory exactness in the immediate future. All

[1] Homann, *Astr. Nach.* No. 2714; Schönfeld, *V. J. S. Astr. Ges.* Jahrg. xxi. p. 58; Vogel, *Astr. Nach.* No. 3150.

[2] *Astroph. Journ.* vol. xiii. p. 80.

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that is needed is a closer and a wider application of means already in the hands of astronomers. Still our curiosity will not even then be satisfied. The value of the two items of information within our reach is indeed incalculable. They are a *sine quâ non* for the furtherance of inquiries into stellar mechanics; are they to be a *ne plus ultra* as well?

The sun, we are well assured, is not travelling along a straight line. The universality of gravitation makes rectilinear movement next to impossible, since no cosmical body can traverse space under the sole guidance of its own primitive velocity. It is true that, supposing primitive velocities altogether abolished (and we know of no necessity for their existence), any number of bodies might be united into a system endowed only with pendulum-like motions. The sun and stars might thus, by an abstract possibility, be totally devoid of advancing or circulatory movements, each swinging for ever to and fro through their common centre of gravity. But it is practically certain that this plan is not realised in the sidereal system.

The path of the sun is then a curve, but a curve most likely of such vast proportions as to remain for ages indistinguishable from a right line. Strictly speaking, its direction is continually changing; the apex of to-day will not be the apex of to-morrow; still less will it be the apex of a million years hence. Yet in a million years, it may quite conceivably not have shifted from its present place in the sky by more than the width of the full moon; and our best determinations still fall far short of the accuracy which would enable us to detect a change of half a dozen times that amount. Directly, that is to say; indirectly, a much more insignificant alteration might disclose itself. We will endeavour to explain how.

Pond, who in 1811 succeeded Maskelyne as Astronomer Royal, made the remark that the sun's motion must produce a kind of secular aberration of light, by which the stars are permanently displaced from their true positions.[1] The well-known consequence of *annual* aberration is to make them appear to describe little ellipses, the semi-axes of which depend upon the ratio of the velocity of light to the velocity of the earth

[1] Liagre, *Bull. de l'Acad.* Bruxelles, t. viii. p. 168, 1859; O. Struve, *Mémoires*, St. Pétersbourg, t. v. p. 106, 6e Série.

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in its orbit. But the sun's orbital movement being conducted, so far as experience yet goes, in one direction, the aberration due to it is in one direction too, and is hence constant, and for the present beyond the reach of observation. It is, however, constant only so long as the movement producing it remains sensibly so. As the latter changes, it will change too, and may in this manner be brought within the domain of human cognisance. For upon the acceleration, retardation, or deflection of the sun's movement systematic changes among the stars should ensue, the nature of which would at once betray their origin.

The total amount of this secular aberration may be roughly stated as one second of arc for every mile per second of the sun's velocity. Hence, stars 90° from the solar apex are pushed forward towards it by about 12″, the effect upon other stars diminishing with the sines of their distances on the sphere from the same point. These aberrational can be distinguished from the parallactic displacements similarly occasioned by their indifference to remoteness in space. Stars far and near, bright and faint, swift-moving and tardy, are equally affected by them. But while it is quite certain that visual disturbances of this kind are produced, their interest must for a long time remain purely theoretical. Indeed, it may well be that the modifications rendering them sensible and instructive, will proceed with such exorbitant slowness that not even astronomical patience will avail to unmask them.

We do not know the plane of the sun's orbit—only the direction of one line in it. And that line, pointing towards the constellation Lyra, makes an angle of about 60° with the sun's equator. Thus, the solar movements of rotation and translation would seem to be unrelated one to the other; and the planetary revolutions to be similarly independent of interspatial travelling. Our whole system is driven obliquely upward by a power which, taking no apparent account of its domestic economy, must have a source disconnected from the originating impulse of the helicoidal gyrations illustrated in Fig. 36, from a diagram by Professor Young.

A remarkable feature of recent improvements in the determination of the sun's course through the heavens has been to reduce to insignificance its deviation from the plane of the Milky Way. This is an implicit testimony to their value.

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It is difficult to conceive that course prescribed otherwise than by the combined attractions of the galactic myriads. The most probable supposition as to the situation of the centre of force swaying our system is that it lies somewhere in the cloudy zone which so enhances the mysterious beauty of our skies. If the orbit we are pursuing be approximately circular, then its centre must be distant by a quadrant of the sphere from the apex — it must lie somewhere on a great circle of which the apex and anti-apex are the poles. Now this great circle cuts the Milky Way at two opposite points in Cassiopeia and Centaur, and there, accordingly, two alternative centres of the solar motion might be looked for. Argelander chose for its position the spot near Cassiopeia marked by the great cluster in the sword-handle of Perseus;[1] but the conjecture made no pretension to scientific authority, and the postulate upon which it was based of the sun's path being at all nearly circular is in truth of a highly precarious nature.

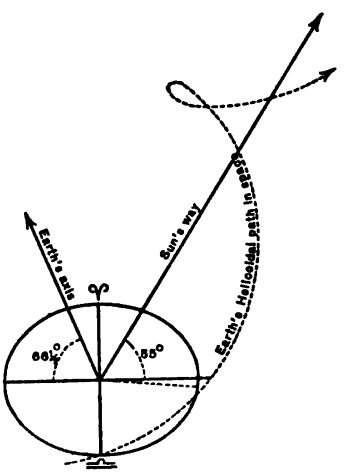

FIG. 36.—The Earth's Motion in Space (Young).

We are even ignorant whether the ascertained translation of our great luminary represents a primary or a secondary order of stellar revolution. It perhaps merely indicates the interstitial movement appertaining to the sun as a member of a restricted group of stars, the common transport of which proceeds undetected in a totally different direction. Hence the possibility, suggested by Herschel, of the presence of a higher kind of systematic parallax than that revealed in the drift of bright stars.[2] And Professor Campbell wrote, after a full century had ripened experience: "The motion of the solar system is a purely relative quantity. It refers to specified groups of stars. The results for various groups may differ

[1] *Mémoires présentés*, St. Pétersbourg, t. iii. p. 602.
[2] *Phil. Trans.* vol. lxxiii. pp. 1276-77.

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widely, and all be correct."[1] So far, however, no tangible evidence has been adduced to show that differences of the kind, grounded in the nature of things, really exist. If they do, they escape through the wide meshes of the nets with which we capture grosser facts.

Progress is here only possible through careful and minute study of the residual movements of the stars—of the movements, that is to say, which remain after the general perspective effect of the sun's motion has been subtracted, and which belong, accordingly, to their individual selves. The questions connected with them which most immediately present themselves are these: Has the sun companions on its journey, or does it travel alone? and, Are real stellar displacements governed by any obvious law?

The great multitude of the stars are, to all appearance, indifferent to the transport of our system. They have clearly no share in it. Just because they stand aloof, and act as indicators of the way, its progress becomes sensible to us. For motion is not alone undiscoverable, it is even unimaginable without some fixed point of reference. Yet we cannot pronounce with certainty against the existence of a particular dynamical bond connecting the sun with some few of the stars, which form with it a company associated by subjection to identical influences, and engaged on the same journey through space. As to the criteria by which such associated stars, if present, can be discriminated from the rest, something will be said in the next chapter.

There, too, we will consider what answer should be given to our second query. A great deal depends upon it as regards our conception of the sidereal universe. Nay, the result of inquiry upon the point has a vital bearing upon the subject we have just attempted, however inadequately, to deal with. For the assumption that the absolute movements of the stars have no preference for one direction over another forms the basis of nearly all investigations hitherto conducted into the translatory advance of the solar system.[2] The little fabric of

[1] *Astroph. Journ.* vol. xiii. p. 87.

[2] Bravais, it is true, discarded the hypothesis of casual proper motions, but had to substitute for it questionable assumptions regarding stellar masses, distances, and velocities.—*Journal de Liouville*, t. viii. p. 435. (See Kapteyn, *Astr. Nach.* No. 3722.)

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laboriously acquired knowledge regarding it at once crumbles if that basis has to be removed. Profitable inquiry into the circumstances of the sun's journey have been rendered feasible by the supposition that, for the purpose in hand, the movements of the stars may be treated as casual irregularities; should they prove to be in any visible degree systematic, the mode of treatment adopted becomes invalid, and its results null and void. The point is then of singular interest; and the evidence bearing upon it deserves our utmost attention.

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CHAPTER XXIV

THE PROPER MOTIONS OF THE STARS

WHEN the relative positions of the stars are compared at considerable intervals of time, they are in many cases found to have undergone small, but unmistakable changes of a seemingly capricious character. These are termed "proper motions" to distinguish them from merely nominal shiftings due to the slow variation of the points of reference which serve to define the places of all the heavenly bodies as seen projected on the inner surface of an imaginary concave sphere. Proper motions are by no means easy to get at. Only from the most delicate observations, and with stringent precautions for bringing those at distant dates under precisely similar conditions, can they be elicited with satisfactory accuracy. Otherwise, some trifling systematic discrepancies in the compared catalogues, or oversights in computation, might simulate genuine effects of movement, with disastrous influence upon sidereal investigations. Hence, proper motions cannot generally be regarded as established unless, in addition to the terminal observations showing a sufficiently marked change of place in the course of thirty, fifty, or one hundred years, at least one intermediate observation is at hand to prove that the suspected motion has proceeded uniformly in the same direction, and is accordingly not the creation of personal or instrumental inaccuracy.

Although not one among the scores of millions of stars can, with any show of reason, be supposed at rest, only ten thousand of the stellar army have, up to the present, shown measurable and progressive displacements.[1] Many of

[1] Dyson, *Observatory*, vol. xxviii. p. 275.

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these, including nearly all the *lucidæ* of the northern hemisphere, were observed by Bradley between 1750 and 1762; in the southern, Lacaille's simultaneous labours serve to authenticate the changes of some three-score of objects to which he devoted especial care. So that a large stock of highly accurate data already possesses an antiquity of one and a half centuries; the catalogues of Piazzi, Lalande, and Groombridge are of two-thirds that age; while multiplied subsequent observations afford a further supply from which fresh and well-determined proper motions are continually being harvested from the seed planted by an earlier generation.

The aspect of the heavens is, to the unaided sense, virtually unchanging. The constellations disclosed at the present time by the nightly withdrawal of the veil of twilight would be familiar, could they revive to survey them, to the watchers from the towers of Babylon. And most of the star-alignments given in our text-books might be as useful to students of celestial physiognomy a couple of thousand years hence as they are to-day. Every one of the indicated stars will indeed most probably, by that time, have shifted its place to the extent of many thousands of millions of miles. Yet so overwhelmingly vast is the sidereal scale that thousands of millions of miles measured upon it sink into insignificance.

Stars advancing in a century as much as 30″, or about $\frac{1}{60}$ the width of the full moon, are counted rapid travellers; and the swiftest class, with secular motions of 100″ and upwards now embraces about one hundred members. Each of these, were it bright enough for ordinary perception, would in a couple of millenniums become very sensibly displaced even to an unskilled observer. But only a small proportion of the quickest stars are visible to the naked eye, and only ten reach the fourth magnitude; hence their shiftings make very little difference in the general effect of the starry skies.

As might have been expected, the stars in most rapid apparent movement are among those nearest to the earth. Vicinity, in fact, and *angular* velocity vary together. Displacements on the sphere are large just in the proportion that the distances of the objects travelling identically in space are small. Were there any approach to uniformity in the real

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velocities of the stars, we could then fairly estimate, from their seeming movements, their relative situations as regards ourselves. But there is no such approach to uniformity. Boundless variety prevails here, as in every other branch of sidereal statistics. Stars with large proper motions are sometimes enormously remote; and, if stars with large parallaxes and little or no movement have not been discovered, it is perhaps because they have not yet been looked for. Their occurrence, for a reason to be presently explained, would be of great interest, and is not unlikely to be certified by measurements on photographic plates.

But, however great the range of variety, it seems certain beforehand that, on the whole, the amount of visible motion in a given number of stars must decrease as their distance increases. And since their brightness falls off at the same time, although much more rapidly, there appears no escape from the conclusion that motion and magnitude must, on a wide average, vary together according to a definite ratio. From stars of the sixth photometric magnitude, for instance, we receive only one-hundredth part of the light sent to us by stars of the first magnitude; they must then, one with another, be ten times more remote. Otherwise, we should be driven to the unwarrantable assumption of a systematic difference of real lustre between apparently large and apparently small stars. But, if the average distance of sixth-magnitude stars be ten times, then their mean motion should be only one-tenth that of stars of the first magnitude. Yet in point of fact this is not so. The proper movements of classes of stars diminish indeed very notably with their brilliancy, but not in the computed proportion. The discrepancy deserves attentive study.

The average proper motion appertaining to the sixth magnitude, as determined directly by M. Ludwig Struve from 647 of Bradley's stars, is $8''$ in one hundred years.[1] Ten times this quantity, or $80''$, *ought* to be the average movement of stars of the first magnitude. But the mean derived from the actually observed shiftings of the twenty brightest stars in both hemispheres is only $60''$.

Stars of the second magnitude are still more noticeably

[1] *Mémoires de St. Pétersbourg*, t. xxxv. No. 3. p. 8.

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inert. They should be, on the photometric scale, 6·3 times nearer to the earth than stars of the sixth magnitude. This would give, for their mean secular motion, $8'' \times 6{\cdot}3 = 50''{\cdot}4$. Twenty-two such stars, however, from Bradley's and the Pulkowa catalogues, show no more than $1{\cdot}7''$. And even this low figure more than doubles that representing the average movement of forty-two southern stars, of 1·7 to 2·7 magnitudes, forming a descending sequence with the ten of first magnitude. Nor is this average improved by considering only the first twenty on the list, from β Crucis of 1·7 to κ Orionis of 2·2 magnitude. The swiftest of these (γ Crucis) travels only $20''$ a century; taken all round, they move $8''$, or with exactly the speed of stars presumably more than six times as remote!

The anomaly of low apparent velocity is accentuated by the close agreement between M. Struve's results for stars from the second to the fourth rank inclusive. A glance at the accompanying Table from his Memoir will serve better than verbal explanation to make the matter intelligible. The object of its compilation was to exhibit the divergence between the proper motions actually determined and those computed from the basis of the mean secular displacement corresponding to the sixth magnitude. In the fourth column, however, we have substituted figures derived from strict photometric star-distances for others depending upon a scale of distances involving dubious assumptions.

Table of Secular Mean Proper Motions of all Bradley's Stars differing by not less than eight-tenths of a magnitude.

Magnitude.	No. of Stars.	Mean Motion.	
		Observed.	Computed.
1	9	66″·5	80″·0
2	22	17″·2	50″·4
3	51	16″·5	31″·8
4	106	16″·2	20″·6
5	318	8″·3	12″·7
6	647	8″·0	8″·0
7	92	6″·8	5″·0
8	11	12″·5	3″·2

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It will be observed that the velocity of each order brighter than the sixth falls short of its theoretical amount, while that of the fainter orders exceeds it. We hasten to add that (as M. Struve points out) little or no dependence can be placed on the above mean rate of eighth-magnitude motion deduced from measurements of only eleven objects.

And now, what are we to think? How can we account for the indicated deficiency of proper motion in the brighter stars? Three possible explanations present themselves. It is conceivable that stars, say of the sixth and seventh, are really smaller or dimmer bodies on an average than stars of the first and second magnitudes, and are consequently less remote than they should be on the more natural supposition of their equality. Their diminished distance would then at once render their extra celerity intelligible. Again, there *may* be a systematic increase of motion outward from the sun, producing in the fainter stars preponderating rates of displacement. Or thirdly, there may exist a special class of stars deficient in light-power, but travelling with exceptional speed, by the influence of which the balance of seeming swiftness is turned in favour of the less brilliant classes of stars.

Of these alternatives, the second may be dismissed as being at variance with our best information. There remain the first and third, neither of which, certainly, represents the whole truth, although each not improbably corresponds to some partial aspect of it. A harmonious adjustment of their claims to credibility is thus difficult to bring about amid the jostling of mutually adverse inferences. Professor Kapteyn has established, by diligent sorting and sifting of multitudinous data, the broad principle that proper motion varies in amount in the due proportion of distance. But he has also established that magnitude is no safe index to distance, apart from the discrimination of spectral types. Stars of Sirian and helium quality taken all round are, in fact, 2·7 times more remote than solar stars of the same photometric rank. The former accordingly shine with a seven-fold intensity comparatively to the latter. Hence, variations in the distribution of the spectral genera may greatly perturb the methodical progression of observed proper motions. Here is one obvious source of anomalies; and the large relative

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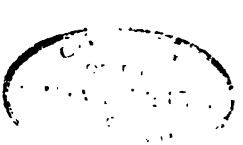
number of "white" stars included among the four or five dozen most lustrous gems of the firmament (see Appendix, Table I.) should be noted in this connection.

It must further be inquired whether stars of all classes, and situated in all parts of the sidereal world, are equally mobile? Kapteyn and Newcomb agree that systematic differences are unapparent; but line-of-sight measures furnish evidence of a more direct kind than that examined by them. Now, in classifying the radial velocities of the 280 stars employed in determining the solar translation, Professor Campbell found their rate to increase notably with faintness.[1] Within the scope of his investigation, the result was assured; but its scope was restricted. Individual peculiarities of the stars embraced by it may have been concerned. This requires a word of explanation. Messrs. Frost and Adams have gathered strong indications, from their work with the Bruce spectrograph on the 40-inch Yerkes refractor, that helium stars really travel in space more slowly than other stars.[2] Hence, if objects of this kind were represented more largely among the bright, than among the fainter stars on Professor Campbell's list, the discrepancies in their rates of movement would be accounted for. That their true explanation must be sought in some such special circumstance rather than in any systematic diversity, is practically certified by exhaustive statistical inquiries, and more particularly by Professor Comstock's study of a collection of stars ranging from the ninth to the twelfth magnitude.[3] Their average linear velocity, estimated by Kapteyn's unexceptionable method, agreed almost precisely with that of Campbell's stars, notwithstanding their photometric inferiority to them, in the mean, by no less than six magnitudes. Summing up, then, it appears that stars of the same spectral type, wherever situated, possess, in a general way, similar movements; but that helium stars are perhaps genuinely slow in pace; while Sirian stars seem more leisurely travellers than solar, merely because they show equally bright at a much greater distance.

Yet the preponderance of small stars in every enumeration

[1] *Astroph. Journ.* vol. xiii. p. 85.
[2] *Ibid.* vol. xvii. p. 246; *Decen. Publ.* vol. viii. p. 105.
[3] *Astr. Journ.* No. 558.



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of rapid proper motions is a challenging fact. Its accepted explanation is that the average of stellar size is low—that triton-suns are few, minnows numerous. Possibly, however, their deficiency is in light rather than in mass. A sample of the evidence bearing on the point is collected in Table VI. of our Appendix, which gives the magnitudes and motions of the thirty quickest stars of our acquaintance. More than half are invisible to the naked eye; the four heading the list have a mean magnitude of 7·3; no less than eleven range from the eighth to below the ninth, while only two stars of the first, *none* of the second, and one of the third magnitude are included in the conspectus. The largest proper motion yet detected belongs to an 8·5 magnitude star situated in the southern constellation Pictor. Its discovery in 1897, in which Kapteyn and Innes co-operated,[1] was one of the many fruits of sidereal knowledge plucked during the preparation of the Cape Photographic Durchmusterung. It superseded as the champion racer, and far outstrips 1830 Groombridge, an insignificant star in the Great Bear, picked out by Argelander in 1842 for a rate of progress which would carry it in 185,000 years round the entire sphere, or in 265 over as much of it as the sun's diameter covers. The corresponding annual advance amounts to 7″; and it is very nearly equalled by two small southern stars observed by Gould during his stay at Cordoba. One is a 7·2 magnitude star in the Southern Fish (Lacaille 9352), the other, one of 8·2 in the constellation Sculptor. Next on the roll comes 61 Cygni with a proper motion of 5″·2; and *α* Centauri, with 3″·7, has eleventh place. Double stars are frequently conspicuous for rapid movement; and it is noticeable that three out of the four first-magnitude stars with proper motions exceeding one second of arc yearly—namely, Sirius, Procyon, and *α* Centauri—are binaries. Struve's general inference as to the quicker translation of multiple than of simple objects, has received much support from further experience.[2]

The "proper motions" of stars include, as was explained in the last chapter, an apparent, as well as a real element; they consist, in technical phraseology, of the *motus paral-*

[1] *Astr. Nach.* No. 3466 (Kapteyn); *Observatory*, vol. xxii. p. 99 (Gill).
[2] Gavin J. Burns, *Astroph. Journ.* vol. xvii. p. 67.

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lacticus, optically transferred to the whole stellar multitude from the single real motion of the sun, and the *motus peculiaris*, belonging to each individual star. The separation of these two constituents, blended together on a cursory inspection, is a necessity for progress. This is what Kapteyn's mode of analysis aims at, and in a measure accomplishes. For the motion of a star in a direction perpendicular to that of the sun's route is altogether its own; it is an objective fact; and the comprehensive study of such components of stellar velocities, purified by a sort of "fractionation" from parallactic ingredients, affords undoubtedly the most promising means of gaining insight into the general plan of celestial revolutions.

But the *motus peculiaris* itself is only a projection upon the sphere of a line of travel which may make any angle with the line of sight. Its amount then varies with direction no less than with distance and actual velocity. A star may appear devoid of motion simply because the whole of it is "end-on"; while the movements of others seem large because, lying square to the line of sight, they are completely effective for apparent displacement. Here, just where ordinary observation is baffled, the prismatic method comes to the rescue. The spectroscope "takes up the running" for the telescope.

The alliance could not have been rendered effective but for the momentous improvements effected late in the nineteenth century in the processes of celestial photography. The prerogatives of the camera in this line of work are enormous. Not only do the worst mischiefs of atmospheric disturbance vanish with its employment, but the upshot of measurements executed upon one line can be checked or ratified by comparisons with other lines in the same spectrum, and on the same plate. Where motion is in question, all must be equally affected by it; hence perfect security against illusion is afforded. The full realisation of these advantages through Vogel's skilful use of the spectrographic apparatus erected by him at Potsdam in 1888,[1] thus constituted an advance of first-rate importance in practical stellar astronomy.

The example thus set has been widely followed—in America, at the Cape, in Europe at Cambridge, Pulkowa, and

[1] *Monatsberichte*, Berlin, March 15, 1888, p. 397.

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Paris. Numerous discoveries of spectroscopic binary systems ensued, and have been adverted to in an earlier chapter; but they came mostly as unsought gratuities, and were fortunately not as effective as the apples of Atalanta in diverting endeavour from an ultimate goal. Researches into sidereal construction are essentially of a statistical character; they demand large bodies of data; and those concerning radial velocities must be rendered comparable in abundance to those already accumulated of the projected movements of the stars, before such researches can be prosecuted with entire success. Eventually, too, radial velocity can be made to serve as a test of mean parallax. It may fairly be assumed that stars travel on an average with equal speed along each of the three co-ordinates of cubical space. Comparing then the mean radial speed in miles per second of a given group of stars with their mean displacements in seconds of arc along circles of declination or right ascension, we at once learn their mean distance, since we thus virtually translate angular into linear displacements.[1] It is true (as can be seen from an inspection of Table VII. in our Appendix) that much swifter rates of stellar transport have been determined in a tangential direction than in the line of sight; but the inequality may be an accident of investigation which its further progress will redress. Meanwhile, there is much reason to believe that no general disparity of the kind subsists. Estimates of the average total velocity of the stars in space were derived by Kapteyn and Newcomb from their observed proper motions, and by Campbell from their measured rates of approach or recession. They agreed almost exactly. With reference to a fictitious stationary centre of the stellar assemblage, a medium star is displaced by 21 or 22 miles a second, 12½ miles being the rate of our sun. We are accordingly borne along in the train of a somewhat sluggish luminary.[2]

Table VII., 2, gives a list of stars with thwartwise movements exceeding 25 miles a second. They are sometimes called "runaways," because their headlong course seems hardly compatible with entire subjection to the sway of gravity.

The first of these startling examples to become known

[1] Kleiber, *Astr. Nach.* No. 3087.
[2] Newcomb, *The Stars*, p. 304.

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was 1830 Groombridge. The large proper motion and small parallax of this star compel the ascription to it of a speed—taking into account only that part of it lying square to our view, of at least 150 miles a second—a speed uncontrollable, according to Professor Newcomb, by the combined attractive power of the entire sidereal universe. For his calculations show that the maximum velocity attainable by a body falling from infinity towards and through a system composed of 100,000,000 orbs, each five times as massive as our sun, and distributed over a disc-like space 30,000 light-years in extent, would be 25 miles a second.[1] But 1830 Groombridge possesses more than six times this speed; and because velocity varies with the square root of the attracting mass, a world of stars of fully thirty-six fold the potency of that assumed as probable would be required to set this object moving as it does unquestionably move!

Now the velocity producible by an attractive system is the limit of the velocity it can control—that is, bend into a closed curve. It is then certain that unless the stellar system possesses what we may call occult gravitational energies, the star in question cannot be one of its permanent members. Virtually in a straight line and without slackening, it will pursue its course right across the starry stratum it entered ages ago on its unknown errand, and will quit ages hence to be swallowed up in the dusky void beyond. There is, however, an alternative supposition. The star *may* be acted upon by unknown compulsive influences.

Lord Kelvin has lately estimated the quantity of gravitating matter needed to produce velocities such as the generality of stars exhibit. He finds it to be that of a thousand million suns like our own, evenly distributed throughout a sphere with a radius of 3262 light-years.[2] A prodigious lapse of time would further be needed for the development, by continuous acceleration, of the observed higher rates of speed; nor can we be quite sure that even these heroic measures would suffice to produce them. Yet they are patent, and not extremely scarce. Groombridge 1830 is no longer the only "runaway" of our acquaintance.

[1] *Pop. Astronomy*, p. 499.

[2] *Report Brit. Ass.* 1901, p. 563; *Nature*, vol. lxiv. p. 626.

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Linear stellar speed, apart from that share of it directed along the line of sight, exceeds Newcomb's computed maximum of 25 miles a second in about one-third of the cases in which it has been ascertained, and the excess is here and there very large. Arcturus, for instance, travels at the tremendous rate of 257 miles a second, μ Cassiopeiæ at 113; while five southern stars progress by 60 to upwards of 80 miles per second.

"Flying stars" can then no longer be regarded as mere intruders into stellar society. Whether or not belonging to it "for better for worse," they evidently at present form an important part of it, and the problem they present cannot be excluded from a general consideration of sidereal mechanism. Indeed they furnish a most significant index to the workings of its secret springs. They pursue their careers, so far as observation can yet tell, in right lines, and at a uniform speed. Their high velocities would be otherwise less perplexing; for they might plausibly be attributed to the powerful attraction of invisible bodies in their neighbourhood, representing, by analogy, the rush past the sun of highly eccentric comets. But the evidence is wholly against any such hypothesis. All proper motions known to us—whether of single stars or of the centres of gravity of multiple stars—are sensibly rectilinear. The centres of curvature, presumably, of the imaginary lines traced out by them, are inconceivably remote. A straight line is only part of the circumference of a circle of infinite radius.

The fact accordingly confronts us that not a few of the stars possess velocities transcending the power of government of the visible sidereal system. Is that system, then, threatened with dissolution, or must we suppose the chief part of its attractive energy to reside in bodies unseen, because destitute of the faculty of luminous radiation? The presence of many such bodies is unquestionable; and those of which we take inferential cognisance may be few compared to the multitude wholly beyond our ken. The power of the universe is certainly reinforced by the dark stars it includes; but to what extent is unknown; and the uncertainty helps to maintain inviolate the final secrets of our cosmical environment.

Physical peculiarities are not, in any obvious way, related

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to excessively rapid movements. Arcturus is a solar star, showing prominent titanium-absorption, and apparently well-advanced towards the Antarian stage. Its mass is presumably enormous, since its light-power must be equivalent to that of twelve to thirteen hundred suns! Its nearest competitors in swiftness, 1830 Groombridge and μ Cassiopeiæ, are, on the other hand, comparatively unpretending orbs; and neither differs markedly in spectral quality from our sun. Indeed, the solar type appears to be more often associated with high velocities than any other. Stars with banded and gaseous spectra, and variables of all classes mostly exhibit but slight signs of displacement; but this may be an effect of remoteness, rather than of genuine inertness.

An unmistakable connection, however, exists between proper motion and sidereal locality. The late Mr. Proctor drew attention to the prevalence in certain regions of the sky of what he termed "star-drift."[1] Here and there, unanimity is, to some extent, substituted for the caprice superficially characteristic of the "peculiar" movements of the stars. Amid seeming confusion, order and purpose by glimpses reveal themselves. Battalions of stars—"flying synods of worlds"—regardless, as it were, of the erratic flittings of the casual surrounding crowd, march in widely extended ranks, by a concerted plan along a prescribed track, under orders sealed perhaps for ever to human intelligence.

Among the stars situated between Aldebaran and the Pleiades, there is little relative movement. They all drift in company towards the east, by about 10″ to 20″ in a century. Not, it is true, along strictly parallel lines. A fresh investigation by M. Weersma[2] of 66 members of the Hyades group has brought to view considerable divergences. Dr. Downing's discussion,[3] too, intimates very clearly the division of the main cluster into subordinate families, travelling to some extent on their own initiative. The general tendency of their course is no doubt largely due to the sun's oppositely directed progress.

Five of the "Seven Stars" (*septem triones*) forming the Plough (those excluded being the "Pointer" next the pole,

[1] *Proc. Roy. Society*, vol. xviii. p. 169.
[2] *Groningen Publications*, No. 13, 1904.
[3] *Journal Brit. Astr. Ass.* vol. xv. p. 28.

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and η at the extremity of the handle), were regarded by Mr. Proctor as members of a vast united group advancing with, though outpacing the sun. This remarkable inference has been endorsed by Professor Newcomb;[1] and the reality of the visible flow of movement was substantiated by spectrographic evidence obtained at Potsdam, showing that the stars in question are approaching the earth with a common velocity of about 18 miles a second.[2] The system they form has been roughly estimated by Dr. Höffler[3] to be situated at a distance of 200 light-years, whence it follows that each must greatly exceed our sun in radiative splendour. One of these linked orbs, moreover, carries with it, as our readers are aware, three dependent stars, namely, the Rider-star Alcor, a slowly revolving telescopic attendant, and a more intimate associate spectroscopically revealed.

It is scarcely likely that the combination is self-centred. Concordant motion does not necessarily imply the mutual revolution of the objects to which it belongs. What it does imply is their dynamical connection. But that connection need not be of the kind exemplified close at hand by the earth and moon. It may rather be such as prevails between the earth and Venus, or between Jupiter and Saturn. The group in Ursa Major, it is safe to assert, includes examples of both kinds of relationship. Of the movements of two satellites, Mizar (ζ Ursæ) is the undoubted mainspring. The status of Alcor is dubious. Its path at present appears strictly rectilinear; but latent curvature relative to the large adjacent star may in time become sensible. About the personal independence, however, of all the rest of the company there can be no question. Although dominated by the same influence, they advance each on its own account; nor can their relative situations be looked upon as beyond the reach of change. Ultimately, the bond of union between them will perhaps even cease to be traceable. Slight inequalities betraying differences in the period of revolution round the same remote centre may easily co-exist with what is known as common proper motion. Such discrepancies can alone hold the stars affected by them aloof from binary com-

[1] *The Stars*, p. 80.

[2] H. C. Vogel, *Publicationen*, Bd. vii. Th. i. p. 154.

[3] *Astr. Nach.* No. 3456.

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bination. While travelling along parallel lines, they have still a relative velocity exceeding, at their distance apart, the power of their mutual gravitation to sway into an ellipse. One must hence fall very slowly behind the other, as Saturn falls behind Jupiter after conjunction. Evidence of their affinity is then only temporarily accessible to us. After many ages it will evade recognition. There may be, probably are, in distant parts of the sky, stars revolving in boundlessly spacious orbits round the same focus of attraction with the stars of the Plough; but we have no means of identifying them.

"Partial systems," governed presumably from without, are of tolerably frequent occurrence. The first to become known was discovered by Bessel in 1818.[1] It is composed of a fifth and a seventh magnitude star, known respectively as 36 A Ophiuchi and 30 Scorpii, thirteen minutes of arc apart, yet endowed with an accordant movement of 1″·25 yearly. The former star has a close attendant; and an intermediate minute object also forms part of the company.[2] Another interesting quadruple group was detected by Flammarion in 1877.[3] Two couples in the Swan, one revolving, the other in appearance fixed, separated by an interval of 15′, drift together slowly southward in a direction nearly perpendicular to the line of march of the sun. Their movement is hence "proper" to themselves, perspective effects being unconcerned with it. The stationary pair is the fifth-magnitude yellow star, 17 Cygni, with its bluish satellite at 26″; the circulating pair consists of two eighth-magnitude stars at 3″, numbered 2576 in Struve's great Catalogue.

A curious instance of concerted movement is afforded by two ninth-magnitude stars in Libra, discovered by Schönfeld in 1881 to progress across the sphere at the exceptionally quick rate of 3″·7 annually.[4] Notwithstanding the wide interval (5′) separating them, their advance seems perfectly harmonious. They flit side by side, as if rigidly connected across a chasm probably some thousands of millions of miles

[1] *Fundamenta Astronomiæ*, p. 311.

[2] Flammarion, *Comptes Rendus*, t. lxxxv. p. 783; *Cat. des Étoiles Doubles*, p. 105; Innes, *Reference Cat.* p. 170 A.

[3] *Comptes Rendus*, t. lxxxv. p. 510.

[4] *Sitzungsberichte Niederrheinische Ges.* Bonn, 1881, p. 172.

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in width. A still wider system, noted by Mr. Innes, is formed by two star-pairs in Toucan.[1] In neither case have measures for parallax yet been executed.

To the question—Has the sun any associate in his journey through space? only a provisional answer can be given. None are known, but investigations on the point are barely nascent. The peculiarities which we should expect beforehand to attend such companion-stars, are comparative proximity and relative immobility. They should have sensible parallaxes and be devoid both of radial and tangential velocity. Neither spectroscopic nor telescopic evidence of motion should be derivable from them. No star up to this thoroughly examined combines these characters; but then they could not possibly be found in the "proper motion" stars chosen by preference as the subjects of parallactic observations. Only in one of the stellar points employed for comparison with 61 Cygni has their presence been suspected. Dr. Schur measured, in 1899, what seemed like a parallactic shift of this nameless star to the extent of $0''{\cdot}6$;[2] and Mr. Crommelin, having deduced for it an evanescent proper motion, threw out the suggestion that it might belong to the sun's bodyguard.[3] The possibility, however, depended upon the verification of the parallax, which is not known to have been effected. When more has been done in photographically registering line-of-sight movements, stars may perhaps be discovered sensibly fixed as regards the sun, because borne along with him at the same translatory speed. The construction of such a group, and the distinctive characterisation of its members, might open up a fascinating branch of inquiry. But its methods cannot well be established until its subject-matter is rendered less evasive.

If the system formed by the stars be destined to permanence in its present shape, some general law of movement must be obeyed by them. Even if its state be one of progressive modification, a definite mode of change ought to become apparent. Local irregularities, however, so effectually disguise the fundamental harmony that its prevalence may long continue a matter of speculative belief.

The assumption is indeed indispensable, as Dr. Schönfeld

[1] See *ante*, p. 97.

[2] *Astr. Nach.* No. 3590.

[3] *Observatory*, vol. xxii. p. 375.

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pointed out in 1883,[1] that the motions of the stars are somehow related to the plane in which the vast majority of them are disposed. For otherwise their actual configuration would be a wildly improbable accident of the time in which we live. The Milky Way, to put it otherwise, should be regarded as an evanescent phenomenon, unsustained by any persistently acting forces, the outcome of a hundred millions of casual conjunctions. If this be incredible (as it surely is) then we are constrained to admit a preference, in the long run, among stellar displacements for the grand level of stellar aggregation. The Milky Way must be, in some true sense, what Lambert called it one and a half centuries ago—the "ecliptic of the stars."

Sir John Herschel imagined the law of harmony to consist in a general parallelism of stellar motions, involving a kind of systematic circulation, as of a solid body round an axis perpendicular to the galactic plane. Innumerable exceptions to any such rule are of course to be found, but they were assumed, in the upshot, to be mutually destructive, the main "stream of tendency" flowing on irrespectively of them. But it is difficult to conceive a physical basis for a quasi-rotational system wholly without warrant from experience. More plausible is M. Ludwig Struve's view that the main part of the revolutions of the stars round their common centre of gravity situated *in* the Milky Way, are performed in planes slightly inclined to that of the zone towards which they are concentrated.[2] His attempt, indeed, to elicit a "rotation-component" from the secular movements of Bradley's stars, proved unavailing. Yet this is not decisive against the truth of an hypothesis compatible with a balanced stellar circulation pursued in opposite senses. An apparent drifting movement, detected by Sir David Gill in 1902,[3] of the brighter stars within a southern zone 12° wide relatively to their fainter associates, involves considerations of a different kind. It has yet to be substantiated. Every imaginable precaution was indeed taken against insidious errors; yet such a phenomenon, if genuine, should almost necessarily be universal; and Pro-

[1] *V. J. S. Astr. Ges.* Jahrg. xvii. p. 255.
[2] *Mémoires de St. Pétersbourg*, t. xxxv. No. 3, pp. 5, 19.
[3] *Astr. Nach.* No. 3800.

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fessor Turner[1] failed to derive from the Oxford zone-plates convincing evidence of its extension to northern stars.

M. Rancken dealt in 1882 with a strictly selected list of stars.[2] He admitted only those within thirty degrees on either side of the Milky Way, and possessed of annual proper motions not exceeding a quarter of a second. The solution of his equations showed these movements to include a common element of very slow progressive increase of galactic longitude. That is to say, the 106 stars considered were being gradually swept along the Milky Way in the direction from Aquila upward towards Cygnus and Cassiopeia, and down past Capella through the Club of Orion towards the Ship. The reality and extent of this flow of displacement will be a matter for future investigation. Should the one be confirmed, and the other ascertained, something like a clue to the labyrinth of stellar movements will have been provided. Perhaps the restricted nature of the inquiry contributed to its success. For the exclusion of large proper motions was the most effective mode of sifting out stars of the solar type, to which they in the main belong. And since this class of bodies are not perceptibly condensed towards the Milky Way, they are unlikely to obey any law of subordination to it in their revolutions. In this line of research, accordingly, as in most others connected with sidereal structure, the discrimination of spectral types is prescribed under penalty of hopelessly confusing the issue.

[1] *Monthly Notices*, vols. lxiii. p. 56, lxiv. p. 3.
[2] *Astr. Nach.* No. 2482.

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CHAPTER XXV

THE MILKY WAY

THE Milky Way shows to the naked eye as a vast, zone-shaped nebula; but is resolved, with very slight optical assistance, into innumerable small stars. Its stellar constitution, already conjectured by Democritus, was one of Galileo's earliest telescopic discoveries. The general course of the formation, however, can only be traced through the perception of its cloudy effect; and this is impaired by the application even of an opera-glass. Rendered the more arduous by this very circumstance, its detailed study demands exceptional eyesight improved by assiduous practice in catching fine gradations of light. Our situation, too, close to the galactic plane is the most disadvantageous possible for purposes of survey. Groups behind groups, systems upon systems, streams, sheets, lines, knots of stars, indefinitely far apart in space, may all be projected without distinction upon the same sky-ground. Unawares, our visual ray sounds endless depths, and brings back only simultaneous information about the successive objects met with. We are thus presented with a flat picture totally devoid of perspective-indications. Only by a long series of inductions (if at all) can we hope to arrange the features of the landscape according to their proper relations.

To the uncritical imagination, the Milky Way represents a sort of glorified track through the skies—

> A broad and ample road, whose dust is gold
> And pavement stars, as stars to thee appear,
> Seen in the galaxy, that milky way,
> Which nightly as a circling zone thou seest,
> Powdered with stars.

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In American-Indian fancy a mysterious "path of souls," its popular German name, "die Jakobsstrasse," recalls the time when it stood as a celestial figure of the way of pilgrimage to Compostella. Similarly, in mediæval England, it got the title of "Walsingham Way" by association with Our Lady's Norfolk sanctuary; while the Dutch dedicated it to St. Hilda, and the Finns set it apart for the flitting processions of birds. More anciently, in the order of ideas initiated by the Accadians, it represented the mystic Snake-river of the abyss[1]—the Homeric Ocean-stream navigated by Odysseus in his voyage to Hades. Superficial impressions of homogeneity are, however, replaced, on closer inspection, by an aspect resembling rather that of a rugged trunk marked by strange cavities and excrescences, and sending out branches in all directions.

The medial line of the Galaxy is scarcely distinguishable from a great circle,[2] although Professor Newcomb's later investigations indicate for it a southward displacement of nearly two degrees.[3] This would imply our position to be somewhat north of the main level towards Coma Berenices; but whether it is central or eccentric there is nothing to show decisively. The movements of the earth bear no obvious relation to the starry collection around it. Neither the equator nor the ecliptic manifests any trace of conformity to its plane. The great circle of the Galaxy is inclined about sixty-three degrees to the celestial equator, which it intersects in the constellations Monoceros and Aquila. It passes in Cassiopeia within twenty-seven degrees of the north pole of the heavens, in Crux, as near to the south pole, while its own poles are located respectively in Coma Berenices[4] and Cetus. Over two-thirds of the celestial circuit, the general unity of this stupendous structure is preserved. Broken, however, near α Centauri by the interposition of a great fissure, it is only regained, after an interval of some 120°, through the reunion, in the neighbourhood of ϵ Cygni, of the separated portions. Involuntarily, the image presents itself of a great

[1] R. H. Allen, *Star Names and their Meanings*, pp. 374-79.
[2] Gould, *Uranometria Argentina*, p. 370.
[3] *Nature*, vol. lxx. p. 308.
[4] R.A. $12^h\ 44^m$ Dec. $+26°\ 48'$ (Newcomb).

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river, forced into a double channel by an encounter with a powerful obstacle, the removal of which lower down permits its waters to flow together again. The intervening long strip of islanded rock and gravel might stand for the great rift between the branches of the sidereal stratum, which, although to the eye, owing to the effect of contrast with the "candid way" on either side, darker than the general sky, is in reality nowhere quite free from nebulous glimmerings. It is encroached upon by fringes, effusions, and filaments, spanned by bridges of light, and here and there it is half filled up by long, narrow, disconnected masses, or luminous *pools*, lying parallel to the general flow of the stream. One such "brilliant and tortuous streak"[1] extends, in almost complete isolation, over nearly 20°, from the tail of Serpens across a corner of the Shield of Sobieski. Moreover, only the more easterly of the two principal branches—that traversing Aquila and the bow of Sagittarius—is continuous. The other, after covering part of Scorpio "with a complicated system of interlaced streaks and masses,"[2] dies out in Ophiuchus, about fifteen degrees south-west of the termination, just at the equator, of the arm sent out to meet it through Cygnus. The gap is, nevertheless, partially veiled by a faint luminous extension from the south, and shows as absolute only over some five degrees of the sphere.

This is not the sole interruption to the course of the Milky Way. Another, visually, though not photographically apparent,[3] cuts sheer across the undivided stream in Argo. Here, at south declination 33°, the formation, Sir John Herschel says, "opens out into a wide, fan-like expanse, nearly 20° in breadth, formed of interlacing branches, all which terminate abruptly in a line drawn nearly through λ and γ Argûs."[4] On the opposite, or eastern side of a moderately broad blank space, a similar assemblage of branches converges upon the variable star η Carinæ. There is an obvious correlation of structure on either side of the chasm; subdivisions mutually correspond; the broken series on one margin is resumed on the other. The impression is strongly

[1] *Uran. Argent.* p. 381. [2] Herschel, *Outlines*, art. 789.
[3] H. C. Russell, *Monthly Notices*, vol. li. p. 496.
[4] *Outlines*, art. 787.

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conveyed that star-strata once united, have here yielded to the influence of some unknown dispersive force or forces, perhaps still in operation. Yet we can scarcely hope ever to command the means of testing the conjecture. For the proper motions of the faint telescopic stars near the edges of the gap, are no doubt of such excessive minuteness that centuries, nay, millenniums may pass before they can become perceptible.

The representation of the Milky Way as a uniform starry stream is purely conventional. Its real texture is of a curdled or flaky description.[1] Between Perseus and Sagittarius, Sir William Herschel counted eighteen luminous patches, "resembling the telescopic appearance of large, easily resolved nebulæ";[2] and his son perceived the lucid ramifications in Sagittarius to be made up of "great cirrous masses and streaks," the appearance, as his telescope moved, being "that of clouds passing in a *scud*, as the sailors call it." Further on, he remarks: "the Milky Way is like sand, not strewed evenly as with a sieve, but as if flung down by handfuls (and both hands at once), leaving dark intervals, and all consisting of 14th, 16th, and 20th magnitudes,[3] down to nebulosity, in a most astonishing manner."[4]

The bright spaces of the galactic zone are commonly surrounded and set off by dark winding channels, and the rapid alternation of amazingly rich with poor, or almost vacant patches of sky, is a constantly recurring phenomenon,[5] associated by Mr. Maunder[6] with slow processes of stellar agglomeration. The most remarkable instance occurs in the Southern Cross, the brilliant gems of which emblazon a broad galactic mass very singularly interrupted by a pear-shaped black opening eight degrees long by five wide, named by early navigators the "Coal-sack." This yawning excavation figures in Australian folk-lore as the embodiment of evil in the shape of an Emu, who lies in wait at the foot of a tree

[1] Houzeau, *Uranométrie Générale*, p. 16, 1878; Klein, *Wochenschrift für Astr.* 1867, p. 288.

[2] *Phil. Trans.* vol. civ. p. 282.

[3] Herschel's "20th magnitude" corresponds approximately with the 14th on the photometric scale.

[4] *Cape Observations*, p. 388.

[5] Herschel, *Outlines*, arts. 790, 797.

[6] *Knowledge*, vol. xviii. p. 36.

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represented by the stars of the Cross, for an opossum driven by his persecutions to take refuge among its branches.[1] The legend reads almost like a Christian parable. The denudation of the Coal-sack is, however, shown by Mr. H. C. Russell's photographs to be complete only towards its northern end.[2] To the south, a considerable invasion of small stars modifies the contrasting darkness.

Partial galactic vacuities, evidently of the same nature with the southern Coal-sack, occur elsewhere, notably in Cygnus; but they are inconspicuous to casual observers. A remarkable doubly perforated star-cloud is exhibited in Plate XIX. from a photograph taken by Professor Barnard in 1892. It makes part of the vivid scenery of the Milky Way in Sagittarius.

An admirable delineation of the formation, so far as it is visible in the northern hemisphere, was completed at Parsonstown in 1889 by Dr. Otto Boeddicker, after five years of labour, amid climatic conditions of the least propitious sort. The general effect may be best described as that of a thick *stem* of light, closely set with curvilinear ramifications; the stem itself being riddled with dusky convolutions, intricate passages, and "horse-shoe" or "key-hole" apertures, separated by lustrous wisps and nebulous "pointed arches." The circumstance that "feelers are thrown out towards nebulæ and clusters,[3] is of profound interest. Thus a feeble branch starting from α Cassiopeiæ terminates at the Andromeda nebula. The Pleiades stand at the peaked summit of a dim vault springing, on one side, from near β Tauri, on the other, from ϵ Aurigæ. The Hyades are separately involved; Præsepe is all but reached by a long streamer issuing from the vicinity of β Canis Minoris; while a thin sinuous effusion, perhaps of a spiral nature, includes the great nebula in its sweep through Orion. The subject was next prosecuted by M. Easton of Rotterdam. His galactic charts[4] are of high authority; and, following up the initiatory efforts of M. Houzeau, he has lately studied, with instructive results, the intimate structure and sidereal relations of the great zone by

[1] MacPherson, *Journ. R. Soc. N.S. Wales*, 1881, p. 72.
[2] *Monthly Notices*, vol. li. p. 40. [3] *Ibid.* vol. l. p. 12.
[4] *La Voie Lactée*, Paris, 1893.

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means of "isophotal curves,"[1] or contour-lines of luminosity. Visual records, however, of barely perceptible details cannot be entirely satisfactory, their agreement being impaired by individual diversities both of purpose[2] and of faculty; and they have been largely, though not wholly superseded, by the promptly-secured impressions of the impartial and impersonal sensitive plate.

The Milky Way varies greatly in lateral extent. A brilliant stream no more than three or four degrees wide where it enters the Cross, it expands to fully twenty-two degrees in the bifurcated section stretching from Ophiuchus to Aquila. At some spots, too, the nebulous effect to the eye fades away imperceptibly along the margins;[3] at others, the line of demarcation is so sharp that a telescope may have one-half of its field crowded with galactic stars, while the other half is well-nigh blank.[4] A definite semi-circular boundary, for instance, limits the formation near ζ Aquilæ; its southern edge in Ophiuchus was remarked by Sir John Herschel, as "terminated by an irregular nebulous fringe as if lacerated";[5] and marginal projections, knobs, and bristling outliers are easily perceptible elsewhere. The prevalent rule seems to be that the smaller the stars considered, the more abrupt is the commencement of the Milky Way; while a more and more gradual condensation accompanies each step upward in brightness.[6]

Sir William Herschel was perfectly satisfied that, with his 20-foot reflector (equivalent to a modern refractor about 14 inches in aperture), the Milky Way was, in general, "fathomable." The stars composing it, that is to say, were of definite numbers, and appeared projected upon a perfectly black sky. But this was not so everywhere; certain parts completely baffled the penetrative faculty of his instrument. One such was met with in Cepheus, where he found the small stars to become "gradually less till they escape the eye, so that appearances here favour the idea of a succeeding, more

[1] *La Distribution de la Lumière Galactique*, Amsterdam, 1903.
[2] *Ibid.* p. 7.
[3] W. Herschel, *Phil. Trans.* vol. civ. p. 283.
[4] Proctor, *Universe of Stars*, p. 86.
[5] Klein, *Wochenschrift*, 1867, p. 285; J. Herschel, *Cape Results*, p. 389.
[6] Celoria, *Memorie del R. Istituto Lombardo*, t. xiv. p. 837.

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Perforated Galactic Group in Sagittarius. Photographed by E. E. Barnard.

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distant clustering part." And he remarked, in exploring between Sagitta and Aquila, that "the end of the stratum cannot be seen."[1] Again, in the galactic branch traversing Ophiuchus, Sir John Herschel encountered "large milky nebulous irregular patches and banks, with few stars of visible magnitudes"; he described "a very large space" of the Milky Way in Sagittarius as "completely nebulous like the diffused nebulosity of the Magellanic Cloud";[2] and observed a similar spot in Scorpio, "where, through the hollows and deep recesses of its complicated structure, we behold what has all the appearance of a wide and indefinitely prolonged area strewed over with discontinuous masses and clouds of stars which the telescope at length refuses to analyse."[3]

Even with the best telescopes of recent construction, this perplexing and indeterminate aspect cannot be altogether got rid of. Professor Holden could obtain with the 36-inch Lick achromatic directed to the Milky Way "no final resolution of its finer parts into stars. There is always the background of unresolved nebulosity on which hundreds and thousands of stars are studded—each a bright, sharp, separate point."[4] The lingering nebulosity was strongly indicated to be of stellar nature, but whether it was due to the presence of innumerable small stars mixed up in the same region with larger ones, or to the indefinite extension into outer space of galactic agglomerations could not be pronounced off-hand.

The explanations attempted of these complicated phenomena may be divided into disc-theories, ring-theories, and spiral-theories. The "disc-theory" of the Milky Way was first propounded by Thomas Wright of Durham in 1750. He supposed all the stars to be distributed in a comparatively shallow layer, producing an annular effect by its enormous lateral spread. Irregularities, he thought, were partly due to our eccentric position within the stratum, partly to "the diversity of motion that may naturally be conceived amongst the stars themselves, which may, here and there, in different parts of the heavens, occasion a cloudy knot of stars."[5]

[1] *Phil. Trans.* vol. cvii. p. 326.
[2] *Cape Observations*, p. 389.
[3] *Outlines of Astr.* art. 798.
[4] *Sid. Mess.* August 1888, p. 298.
[5] *An Original Theory of the Universe*, p. 63.

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To this view Sir William Herschel gave wide currency and apparent stability by the application to its support of his ingenious method of "star-gauges." By counting the stars simultaneously visible with his great reflector in various portions of the sky, he showed that their paucity or abundance depended upon the situation of the gauge-fields relative to the Milky Way. In its neighbourhood, stars were copiously, away from it, they were sparsely distributed. And this by a regular progression of density from the galactic poles to the galactic equator, the latter region being on an average thirty times richer than the former. Now, if we were to admit, as Herschel did, a nearly equable scattering of stars in space, there would be no alternative but to suppose the sidereal system extended in any direction proportionately to the number of stars seen in that direction. Their crowding should, *on that hypothesis*, be purely optical—the effect of the indefinite spreading out in the line of sight of their evenly serried ranks. Sounding the star-depths upon this principle, Herschel measured the length of his line by their seeming populousness, and constructed, from the numerical data thus obtained, the "cloven disc" model, long accepted as representing the true form of the stellar universe.

But his own observations at the very moment of enouncing this theory, fatally undermined it. Already, in 1785, he remarked that two or three hundred "beginning, or gathering clusters," might be pointed out in the galactic system, and he surmised its eventual separation, "after numbers of ages," into so many distinct "nebulæ."[1] "Equable scattering," then, was an ideal state of things long since abolished by the "ravages of time." The conviction that such was the case grew with his experience. "The immense starry aggregation" of the Milky Way, he wrote in 1802[2] "is by no means uniform. The stars of which it is composed are very unequally scattered, and show evident marks of clustering together into many separate allotments." Nor did he fail to perceive, from the gradual increase of brightness towards the centres of these "allotments," that they tended to assume a spherical form, and thus suggested "the breaking-up of the Milky Way, in all its minute parts, as the unavoidable consequence of the

[1] *Phil. Trans.* vol. lxxv. p. 255. [2] *Ibid.* vol. xcii. p. 495.

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clustering power arising out of those preponderating attractions which have been shown to be everywhere existing in its compass."[1] The formal announcement of his conviction "that the Milky Way itself consists of stars very differently scattered from those which are immediately about us,"[2] amounted to a recantation of the principle of star-gauging.

With it disappeared from Herschel's mind the conception of an optically-produced galaxy. In his ultimate opinion the actual corresponded very closely with the apparent structure: it was composed, that is to say, mainly, if not wholly, of real clouds of stars. Credit was thus restored to the early impression of Galileo, who in 1610 described the Milky Way as "nothing else but a mass of innumerable stars planted together in clusters."[3]

Wilhelm Struve's[4] effort towards the reorganisation of the stratum-theory, though aided by all the resources of his great ability and address, could scarcely be counted as a step in advance. Substituting for the hypothesis of equable distribution that of concentration in parallel planes, he imagined the average interval of space between the stars to diminish regularly with approach to the central horizon of the system. The swarming aspect of the Milky Way was hence interpreted as agreeing with fact, but the annular appearance as being illusory. Of illimitable dimensions, the system was conceived to stretch away, still preserving its specific character, to an infinite, or at least unimaginable remoteness, comparatively narrow *visual* bounds being set to it by a supposed extinction of light.

But the quasi-geometrical regularity of Struve's galaxy is belied by innumerable details of the original. The swell of the tide of stars towards the galactic plane is neither uniformly progressive,[5] nor does it proceed without conspicuous interruptions. Thus, the region near the horns of Taurus, although close to the Milky Way, is absolutely the poorest in the northern hemisphere;[6] and it is matched in the southern[7] by

[1] *Phil. Trans.* vol. civ. p. 282. [2] *Ibid.* vol. xcii. p. 480.
[3] *Sidereus Nuncius*, trans. by E. S. Carlos, p. 42.
[4] *Études d'Astronomie Stellaire*, 1847.
[5] C. S. Peirce, *Harvard Annals*, vol. ix. p. 174.
[6] Argelander, *Bonner Beob.* Bd. v. *Einleitung*; Proctor, *Universe of Stars*, p. 32. [7] Thome, *Cordoba Durchmusterung*, Introduction.

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an almost clean-swept space in Scorpio, on meeting which Sir William Herschel exclaimed in amazement, "Hier ist wahrhaftig ein Loch im Himmel!" But it is the openings in the formation itself which most decisively negative the stratum-theory in any of its modifications. Is it credible that a boundlessly extended layer of stars should be pierced, in many of its densest portions, by *tunnels* converging directly upon our situation within it?[1] No sane mind, we venture to say, realising all that such an affirmation implies, can assent to it. But, indeed, the entire conformation of the Milky Way—its streaming offsets, convoluted windings, promontories, and sharply bounded inlets, no less than its breaches of continuity—is absolutely irreconcilable with the hypothesis of optical creation out of star-materials equably distributed.

We seem then led to the alternative belief that it is a definite structure, at a definite distance from ourselves—a belief forced upon Sir John Herschel by his Cape experiences, notwithstanding his natural reluctance to drift far away from the position originally taken up by his father. The shape suggested by him for the galaxy was that of "a flat ring, or some other re-entering form of immense and irregular breadth and thickness."[2] Expanded indefinitely along the central plane, the new model scarcely differed from the old except in so far as the idea of homogeneous construction was given up. The disc remained, but with its centre scooped out. The solar system was located in an enormous space of relative vacuity.

The Milky Way, thus regarded, appeared to consist of an indefinite number of stellar collections "brought by projection into nearly the same visual line"—to represent the foreshortened effect (more especially at a particular spot in Sagittarius) of "a vast and illimitable area scattered over with discontinuous masses and aggregates of stars in the manner of the cumuli of a mackerel-sky."[3] But in an assemblage of this nature seen edgewise, a "Coal-sack" would be a phenomenon as anomalous as in a uniform stratum; nor could it, without violent improbability, be conceived of as rent by the colossal fractures dividing the actual Milky Way in Argo and Ophiuchus.

[1] Proctor, *loc. cit.* p. 15. [2] *Outlines*, art. 788.
[3] *Cape Observations*, p. 389.

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To remedy these inconveniences, Professor Stephen Alexander devised in 1852,[1] upon the model of the wheel-shaped nebula in Virgo (M 99), a spiral galaxy with four curvilinear branches diverging from a central cluster formed by the sun and lucid stars. By properly adjusting the mode of projection of these radiating star-streams, the effects of rifts and coal-sacks were duly produced; but the arrangement, however admired for ingenuity, gave no persuasion of reality, and quickly dropped out of remembrance. Essentially different, although with some features in common, was that by which Mr. Proctor replaced it in 1869.[2] Rather than a "spiral," indeed, the new design resembled a bent and broken ring, with long, riband-like ends, looped back on either side of an opening, accommodated to the shape of the gap in the visible structure in Argo. One of these loops, by the apparent intercrossing of its near with its remoter branch, was supposed to generate the Coal-sack in Crux; while the other end, trailing lengthily backward, afforded a deceptive effect of bifurcation. Excessive distance was invoked, as in Professor Alexander's scheme, to explain the cessation of nebulous light in Ophiuchus.

Of the manifold objections to which this hypothesis is liable,[3] only two need here be mentioned. In the first place, it involves a wholly inadmissible rationale of the openings seen in the Milky Way. If these were due to the interlacing by perspective of branches really far apart in space, the enclosing luminous formation should be markedly fainter on one side than on the other. But this is not so. The borders of the southern Coal-sack are approximately of the same brightness all round. A single vivid mass has obviously been the scene of what, in the absence of better knowledge, may be described as an excavatory process.

Again, on the spiral theory, the great rift in the Milky Way should represent the interval between branches mutually disconnected except through the optical effect of projection. But their mutual dependence is manifest. They strike apart

[1] *Astr. Journ.* vol. ii. p. 101.

[2] *Monthly Notices*, vol. xxx. p. 50.

[3] See Mr. J. R. Sutton's remarks, *Illustrated Science Monthly*, vol. ii. pp. 63, 199; *Knowledge*, vol. xiv. p. 41; Easton, *ibid.* vol. xxi. p. 12.

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gradually, and as the result of changing conditions. Premonitory cavities seem to announce their impending separation; and even after it has become definitive, abortive efforts towards reunion are indicated by the correspondence of opposite projections and by the occasional bridging of the fissure. The bifurcation is beyond question a physical reality.

The prevalence of spiral forms among the nebulæ, emphasised by Keeler's photographic explorations, adds weight to the arguments for assigning a more or less similar structure to the great firmamental zone. M. Easton has illustrated the

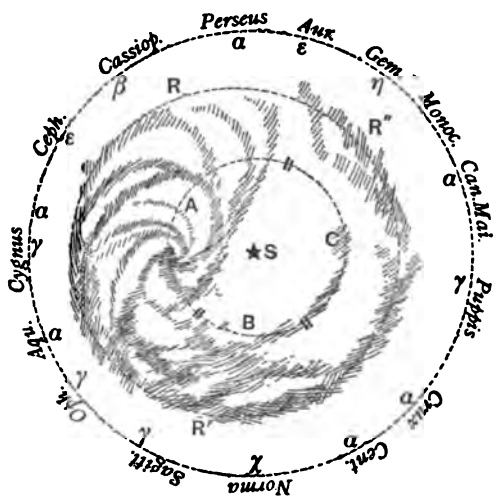

FIG. 37.—The Galactic Spiral (Easton).

subject by a plan-sketch, copied in Fig. 37. It does not profess to give "even an approximate representation of the Milky Way, seen from a point in space situated on its axis,"[1] but merely to indicate a possible mode of distribution of stellar accumulations by which the observed phenomenon might be produced. A remarkable bright patch of the Milky Way in Cygnus serves in it as the nucleus of the convolutions. The sun's position, though central, is detached from them.

Some such design strongly tempts thought. It is recommended by analogy; it is recommended also by its adaptability. A multitude of facts, at first sight incongruous, are combined

[1] *Astroph. Journ.* vol. xii. p. 157.

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by it into plausible unity. The ring-theory may be said to have broken down when Celoria[1] found it necessary to establish a double annular system. His researches, together with those of Plassmann, Seeliger, and Easton, leave no doubt that the various sections of the starry girdle differ prodigiously in distance. Moreover, it seems impossible so to place the sun in such an enclosing structure as to get a reasonable explanation of these differences without having recourse to further complexities of artificial arrangement. True, no design corresponding in any degree with what appears, can be other than intricate. Were it permissible to adopt the opinion that the Milky Way *is* very much what it *seems*, we should describe it as a ring with streaming appendages extending from the main body in all possible directions, some nearly straight towards, or away from us, others at every imaginable angle with our line of sight. The results in perspective foreshortening would evidently, under these circumstances, be highly complex; the eye being presented with groups and streams of stars, immensely various in remoteness, but all projected indiscriminately upon the same zone of the heavens. Thus, while some branches, pursued along their outward course, fade at last into dim nebulosity, other Milky Way groups may be distinguished as bright separate stars, because much nearer to us than the generality of their associates. Closed rings, however, are beginning to appear alien to the cosmic plan of structure. Nebulæ presenting that aspect are, perhaps without exception, resolvable into helical or spiral figures. And it would be hazardous to assert that the Milky Way lies outside the mysterious law imposed upon minor aggregations.

Its internal organisation is of baffling intricacy. It collects within its ample round, there is every reason to suppose, an absolutely endless variety of separate systems. A multitudinous aggregate of individual clusters, it is composed moreover as a whole very much like one single cluster on a colossal scale. Its fringed edges, its rifts and vacuities, are, as we have seen, reproduced in miniature in numberless star-groups. "Rings," and "sprays," and "streams" of stars are unmistakably common to the two orders of formation; and the stellar

[1] *Memorie del R. Istituto Lombardo*, t. xiv. p. 82.

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constituents of both are frequently involved with gaseous nebulæ in a way showing most intimate association by origin and development. The laws then governing stellar aggregation in the one case govern it also in the other; and so, from this direction independently, we again reach Herschel's conclusion that the Milky Way "consists of stars very differently scattered from those which are immediately about us."

But are these stars *suns*, co-ordinate with our own? or must we regard them as comparatively insignificant bodies, sharing a sun-like nature, indeed, but on a far lower level of power and splendour? The question is equivalent to this other perpetually recurring one, What is their average distance from ourselves? In what portion of space do the true galactic condensations occur? How far outward should we have to travel before finding ourselves actually in the midst of the crowded objects producing, to terrestrial observers, the "milky" effect of a nebulous stratum?

Certain knowledge in this matter is not to be had; indications and probable estimates have to take its place. Professor Newcomb, as the upshot of a discussion embracing all the available facts, arrives at the conclusion that the Milky Way, in most of its sections, is no nearer to us than would be signified by a parallax of one-thousandth of a second,[1] corresponding to a light-journey of 3200 years. Now our sun, if thus unimaginably removed into space, would shrink to a star of the fifteenth magnitude; it would seem just one of the grains of shining sand coagulated into heaps out near the confines of the sidereal world. Presumably, then, a large proportion of the lustrous specks forming, in their unnumbered aggregate, the nebulous arch amid the constellations are really suns on the scale of our own. They are, however, pretty evidently intermingled with many smaller globes, and with some vastly larger. M. Easton has succeeded,[2] by detailed comparisons, in establishing a correlation between galactic structures and the stars, from about the sixth to the fifteenth magnitudes, enumerated by Argelander and others. The inference is thus rendered compulsory that a percentage of these comparatively bright orbs are genuine constituents of the clusters

[1] *The Stars*, p. 317.

[2] *Distribution de la Lumière Galactique*, p. 24; Newcomb, *The Stars*, p. 273.

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with which they are collineated. There are besides strong grounds for the belief that many, if not most, of the bluish brilliants giving helium spectra dominate these comprehensive groups. Mr. Ranyard pointed out in 1891,[1] from the evidence of Mr. H. C. Russell's photographs, that the chief luminary of the Southern Cross is centrally situated in a curiously symmetrical little cluster of excessively faint stars; and the irresistible conclusion of its being physically related to them may be safely applied to a number of other lustrous objects of the same spectral class. The range of actual size and splendour, then, among the components of galactic star-drifts is astonishingly great—much greater, in Professor Newcomb's opinion, than in ordinary detached clusters, such as the Pleiades, or the double Sword-handle group. The helium stars of the zone are, indeed, veritable tritons amidst shoals of minnows; they are frequently of a magnitude transcending the powers of imagination to realise, while their dwarfed associates may well be of average sun-like stature.

The Milky Way clouds are not condensed from the general contents of the sidereal heavens; they are markedly distinct. Their spectral peculiarities make this clear. They are built up, essentially and fundamentally, out of Sirian stars;[2] those of the solar and Antarian types seem to be totally absent from them. They include, however, nearly all the helium and bright-line stars that exist; but they are relatively few; they scarcely count as ingredients; they are *rari nantes in gurgite vasto*. Many galactic tracts, too, are suffused with a phosphorescent glow; they harbour nebulous formations which only the photographic camera, through its faculty of persistent gazing, has been able to actualise and define. This surprising characteristic affords an additional proof that cosmic conditions of a special kind prevail in the enigmatical girdle which enclasps the mystery of the universe.

From a most careful study of the Milky Way at Cordoba, where it was seen to peculiar advantage, Dr. Gould inclined to regard it as the product of two or more superposed galaxies.[3] The fact of the two narrowest and brightest, and the two

[1] *Knowledge*, vol. xiv. p. 112.
[2] Pickering, *Harvard Annals*, vol. lvi. p. 25.
[3] *Uran. Argentina*, p. 381.

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most diffused parts lying in pairs opposite to each other is certainly remarkable, and lends some countenance to the surmise that the "necks" in Cassiopeia and Crux really represent the intersections of the two crossed rings visibly diverging in Ophiuchus. M. Celoria, too, as we have seen, adopted the hypothesis of a compound Milky Way, but of such a form as to allow the possibility of one of its constituent annuli being comprehended by the other. The transition to a true spiral shape was thence easily effected, and a wider range of facts was rendered capable of theoretical accommodation. What is unmistakable is that the entire formation, single or compound, while individual and specific, is yet no isolated phenomenon. The contents of the firmament are arranged mainly with reference to it. It is a large part of a larger design exceeding the compass of finite minds to grasp in its entirety.

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CHAPTER XXVI

STATUS OF THE NEBULÆ

THE question whether nebulæ are external galaxies hardly any longer needs discussion. It has been answered by the progress of research. No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of co-ordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation, and stand in ordered mutual relations within the limits of one all-embracing scheme. All-embracing, that is to say, so far as our capacities of knowledge extend. With the infinite possibilities beyond, science has no concern.

The chief reasons justifying the assertion that the status of the nebulæ is intra-galactic are of three kinds. They depend, first, upon the nature of the bodies themselves; secondly, upon their individual stellar associations; thirdly, upon their systematic arrangement as compared with the systematic arrangement of the stars.

The detection of gaseous nebulæ not only directly demonstrated the non-stellar nature of a large number of these objects, but afforded a rational presumption that the others, however composed, were on a commensurate scale of size, and situated at commensurable distances. It may indeed turn out that gaseous and non-gaseous nebulæ form an unbroken series rather than two distinct classes separated by an impassable barrier. Their spectra have perhaps more in common than would, at first sight, be supposed. For the vivid rays of green nebulæ are superposed upon a gauzy background of continuous light,

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which appears to be resolvable into a multitude of bright lines in juxtaposition;[1] and the spectra of white nebulæ show, not a smooth, prismatic gradation, but slight inequalities in the flow of light, indicating effects of absorption, of emission, or of both combined. Before indeed any settled opinion can be formed as to whether these analogies have really the transitional meaning we might be inclined to attribute to them, nebular spectroscopy must be a good deal further advanced than it is at present. But apart from this question, relationship between the various orders of nebulæ is manifest. The tendency of all to assume spiral forms demonstrates, in itself, their close affinity; so that to admit some to membership of the sidereal system while excluding others would be a palpable absurdity. And since those of a gaseous constitution must be so admitted, the rest follow inevitably.

Of the physical connection of nebulæ with particular stars, fresh and incontrovertible proofs accumulate day by day. Nothing can be more certain than that objects of each kind coexist in the same parts of space, and are bound together by most intimate mutual ties. To argue the matter seems, as the French say, like "battering in an open door." We need only recall the stars of the Pleiades, photographically shown to be intermixed with nebulæ, and those in Orion still bearing in their spectra traces of their recent origin from the curdling masses around. The nuclear positions so frequently occupied in nebulæ by stars single and multiple, reiterate the same assertion of kinship, emphasised still further by the phenomena of stellar outbursts *in* nebulæ. The scenes of these *must*, as the late Mr. Proctor insisted, lie within the circuit of the Milky Way, unless we are prepared to assume the occurrence, in extra-sidereal space, of conflagrations on a scale outraging all probability. It has been calculated that if the Andromeda nebula were a universe apart of the same real extent as the Galaxy, it should be situated, in order to reduce it to its present apparent dimensions, at a minimum distance of twenty-five galactic diameters.[2] And a galactic diameter being estimated by the same authority at thirteen thousand light-years, it follows that, on the supposition in question, light

[1] Palmer, *Lick Bulletin*, No. 35.

[2] Weisse, *Schriften Wiener Vereins*, Bd. v. p. 318.

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would require 325,000 years to reach us from the nebula. The seventh-magnitude star then which suddenly shone out in the midst of it in August 1885 should have been an absolutely portentous orb. In real light it should have been equivalent to 762,000 stars like Sirius, or to sixteen million such suns as our own! But even this extravagant result inadequately represents the real improbability of the hypothesis it depends upon; since the Andromeda nebula, if an external galaxy, would almost certainly be at a far greater remoteness from a sister-galaxy than would be represented by twenty-five of its own diameters.

Just as the Milky Way might be described as a great compound cluster made up of innumerable subordinate clusters, so the greater Magellanic Cloud seems to be a gigantic nebula combining into some kind of systemic unity multitudes of separate nebulæ. To the naked eye it shows vaguely a brighter axis spreading at the extremities so as to produce a resemblance to the "Dumb-bell" nebula; photographic exposures bring out unequivocal traces of a spiral conformation; either way it shows signs of definite organisation as a coherent whole; and it includes, strangely enough, among its inmates, a miniature of itself (N.G.C. 1978), but of much greater intensity and distinctness. Sir John Herschel's enumeration in 1847, of the contents of the "Cloud," gave conclusive evidence of the interstellar situation of nebulæ—evidence, the full import of which Dr. Whewell was the first to perceive. Over an area of forty-two square degrees, 278 nebular objects (stars being copiously interspersed) are distributed with the elsewhere unparalleled density of $6\frac{1}{2}$ to the square degree. "The Nubecula Major," Herschel wrote, "like the Minor, consists partly of large tracts and ill-defined patches of irresolvable nebula and of nebulosity in every stage of resolution, up to perfectly resolved stars like the Milky Way, as also of regular and irregular nebulæ properly so called, of globular clusters in every stage of resolvability, and of clustering groups sufficiently insulated and condensed to come under the designation of clusters of stars."[1]

Here then we find—in a system certainly, as Herschel said, "*sui generis*," yet none the less, on that account, instructive

[1] *Cape Results*, p. 146.

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as to cosmical relationships—undoubted stars and undoubted nebulæ at the same general distance from the earth. Some of the nebulæ may indeed very well be placed actually nearer to us than some of the stars; and the extreme possible difference of their remoteness cannot, if the Cloud be approximately globular, exceed one-tenth of the interval between its hither edge and ourselves. We learn, too, the plain lesson that distance is only one factor in the production of irresolvability. For stars in every stage of crowding, from loose groups to the veriest dust-streaks, globular clusters coarse and fine, nebulæ of all kinds and species, range side by side in this extraordinary collection, proving beyond question that differences of aggregation subsist in themselves, and need no additional abysses of space to account for them.

Even, however, if all these mutually confirmatory arguments could be dismissed as invalid, the mode of scattering of nebulæ on the sky-surface would alone suffice to demonstrate their association with the sidereal system. Sir William Herschel was early struck with the occurrence of beds of these objects, preceded and followed by spaces void of stars. So familiar to him was this sequence of phenomena that he would sometimes warn his assistant "to prepare, since he expected in a few minutes to come at a stratum of the nebulæ, finding himself already on nebulous ground."[1] The relation, after a century of partial oblivion, was photographically rediscovered by Dr. Max Wolf. It is curiously exemplified in the star-denuded nidus of the America nebula[2] (see Plate XVIII.), which seems to have absorbed or repelled from its immediate neighbourhood the dense galactic clouds impending towards it. Similarly, a comparatively vacant region encompasses the Orion nebula, within which, nevertheless, stars swarm and flicker after the manner of the components of globular clusters. The replacement of stars by nebulous matter is again conspicuous in Plate XX., which reproduces, by Dr. Wolf's kind permission, a photograph taken by him, July 10, 1904, with an exposure of four hours. The depicted nebula, which had been discovered ten years previously, is about 10′ in

[1] *Phil. Trans.* vol. lxxiv. p. 449.

[2] *Publicationen des Observatoriums Königstuhl-Heidelberg*, Bd. i. p. 181 (Kopff).

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The Cocoon Nebula in Cygnus. Photographed by Dr. Max Wolf, July 10, 1904.

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diameter, of a round shape, and a complex structure. "It is placed centrally," Dr. Wolf writes, "in a very fine lacuna void of faint stars, which surrounds the luminous cloud like a trench."[1] Moreover, this negative "halo forms the end of a long channel, running eastward from the western nebulous clouds and their lacunæ, to a length of more than two degrees." The coexistence in the same sidereal district of nebulæ and stars could not well be asserted with stronger emphasis than by the clearing of a dark fosse for the accommodation of the cocoon-like object in Plate XX.

The larger plan of nebular distribution, as being the inverse to that of stars, partially revealed itself to the elder Herschel; but Sir John first brought into clear view the distinct and striking division of the nebulæ into "two chief strata, separated by the Galaxy." Taking the circle of the Milky Way as a horizon, he remarked that the accumulation of them in Virgo and Coma Berenices "forms, as it were, a canopy occupying the zenith, and descending thence to a considerable distance on all sides, but chiefly on that towards which the (celestial) north pole lies."[2]

This crowding about the galactic pole is less marked in the southern hemisphere, though here too there is a "chief nebular region" approximately corresponding to that in Virgo. The distribution is, however, on the whole much more uniform than in the northern hemisphere, or rather, more uniformly *patchy*, rich districts alternating with more or less ample vacuities. One of these extends about fifteen degrees all round the south pole, the Lesser Cloud marking its edge. The remarkable fact, too, was noticed by Sir John Herschel that the larger nubecula seems "to terminate something approaching to a zone of connected patches of nebulæ," reaching across Dorado, Eridanus, and Cetus to the equator, where it unites with the "nebular region of Pisces." A similar line of communication is less conspicuously kept open with the minor nubecula, and this feature of "streams" of nebulæ with terminal aggregations was considered by Proctor to be distinctive of southern skies.[3] He adverted besides to the coincidence of two of them with stellar "streams" in Eridanus

[1] *Monthly Notices*, vol. lxiv. p. 839. [2] *Cape Results*, p. 137.
[3] *Monthly Notices*, vol. xxix. p. 340.

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and Aquarius, and was struck with a significant deficiency of bright stars over the intervals between nebular groups.

Ampler acquaintance with this class of objects has, on the whole, served to ratify earlier conclusions relative to their mode of scattering. Their overwhelming tendency to congregate about the north galactic pole is accentuated by the results of Dr. Max Wolf's photographic survey;[1] while the presence of a secondary focus of aggregation in Perseus and Andromeda, remarked by Waters,[2] was rendered unmistakable by the subsequent investigations of Stratonoff.[3] M. Easton, discussing the subject with his accustomed thoroughness in 1904, was especially struck with the disturbing influence of the Magellanic Clouds. Hence possibly so fundamental a diversity in the modes of nebular distribution on either side of the Milky Way, that he considers it as "very probable that the structure of the southern galactic sky with regard to the nebulæ differs entirely from that of the northern galactic sky."[4]

The leading facts of nebular distribution were correctly described by Herbert Spencer in 1854. "In that zone," he wrote, "of celestial space where stars are excessively abundant, nebulæ are rare; while in the two opposite celestial spaces that are furthest removed from this zone nebulæ are abundant. Scarcely any nebulæ lie near the galactic circle, and the great mass of them lie round the galactic poles. Can this be mere coincidence? When to the fact that the general mass of nebulæ are antithetical in position to the general mass of stars, we add the fact that local regions of nebulæ are regions where stars are scarce, and the further fact that single nebulæ are habitually found in comparatively starless spots, does not the proof of a physical connection become overwhelming?"[5]

Accompanying, but considerably overlapping the Milky Way along its entire round, is a "zone of nebular dispersion" (as Proctor called it)—a wide track of denudation, so far as these objects are concerned. The nebular multitude shrinks, as it were, from association with the congregated galactic stars. A relation of avoidance is strongly accentuated. But with-

[1] *Report of Königstuhl Observatory* for 1902; *Astr. Nach.* No. 3812.
[2] *Monthly Notices*, vol. liv. p. 527.
[3] Ristenpart, *V. J. S. Astr. Ges.* Jahrg. xxxvii. p. 356.
[4] *Proc. Acad. of Sciences*, Amsterdam, June 25, 1904; *Astr. Nach.* No. 3969.
[5] *The Nebular Hypothesis* (with Addenda), p. 112.

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drawal implies recognition. It implies the subordination of stars and nebulæ alike to a single idea embodied in a single scheme. The range of our possible acquaintance is accordingly restricted to one "island universe"—that within whose boundaries our temporal lot is cast, and from whose shores we gaze wistfully into infinitude.

Dismissing, then, the grandiose but misleading notion that nebulæ are systems of equal rank with the galaxy, we may turn our attention to the problems presented by the peculiarities of their interior situation. When these are subjected to a detailed examination, distinctions become evident between the different classes of nebulæ. Distinctions so marked as to lead almost to their separation.

The "relation of avoidance" to the Milky Way just adverted to prevails *only* among the "unresolved" nebulæ. These, it is true, are the great majority of the entire, so that the conclusion of nebular crowding away from that zone remains unimpeachable. For certain classes of minor numerical, but high cosmical importance, the relation is precisely inverted. Over gaseous nebulæ and clusters, the Milky Way seems to exercise an attractive influence equally strong with its repulsive effect upon nebulæ of other kinds.

Forty out of one hundred and eleven globular clusters belong to the galactic zone,[1] which is hence twice as richly furnished as the rest of the sky with these wonderful objects. And the excess rises to twenty-five times for irregular or nondescript clusters, 434 out of 535 of which—that is, 81 per cent—are located in, or close to, the Milky Way. Many clusters, indeed, obviously form an integral part of the formation itself; of others, it is difficult to decide whether they should be ranked as distinct, or simply as intensifications of ordinary galactic star-groupings. To the latter category almost certainly belongs a collection (M 24) visible to the naked eye as a dim cloudlet near μ Sagittarii, and named by Father Secchi "Delle Caustiche," from the

[1] Taken as of the uniform width of thirty degrees, and covering $\frac{1}{4\cdot5}$ of the sphere. Major Markwick (*Journ. Liv. Astr. Soc.* vol. vii. p. 182) finds the proportionate area of the Milky Way in the northern hemisphere to be $\frac{1}{4\cdot37}$, in the southern $\frac{1}{3}$. Pickering (*Harvard Annals*, vol. xlviii. p. 165) estimates the galactic area at 15,612 square degrees, or $\frac{1}{2\cdot7}$ of the sphere.

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peculiar arrangement of its stars in rays, arches, caustic curves, and intertwined spirals. This again is included in a great oval condensation of galactic stars, obviously endowed with some degree of structural independence.

Gaseous nebulæ, like gaseous stars, are nearly exclusive in their galactic affinities.[1] Very few planetaries can be found at any considerable distance from the favoured zone; the spectroscopic search for stellar nebulæ is fruitless unless within its borders; and they embrace—with one exception—*all* the irregular nebulæ. This single exception is a most significant one. It is that of the "great looped nebula" (see Plate XV.), an important constituent of the greater Magellanic Cloud. Plainly, then, the conditions allowing primitive cosmical matter to remain uncondensed in galactic regions, prevail also in the nubecula. The individuality of its organisation has been strongly accentuated by the discovery, lately made at Harvard College, that very many of the stars contained in it fluctuate rapidly in light.[2] Miss Leavitt's examination of the Arequipa plates yielded at once a harvest of 152 variables; and more doubtless await recognition.

Gaseous and white nebulæ meet on equal terms only in this comprehensive assemblage. The Milky Way is more exclusive. It favours the former class largely at the expense of the latter. Within its precincts only one in sixteen of those dim, often fantastically-shaped, objects is met with, the analysed light of which gives no indication of gaseity, while their even texture, under the highest telescopic powers, suggests no approach to the stage of breaking-up into stars. What then is their nature? Is the difference separating them in appearance from the resolvable aggregations of star-dust, crowding the Milky Way, a difference of distance solely? Are they too clusters beyond the reach, through remoteness, of effective scrutiny? There is nothing in their aspect to preclude this supposition. So far as observation can tell, they may be of stellar composition. Only it is not easy to understand why nebulæ situated near the galactic poles should be immensely and consistently more distant than nebulæ thronging the vicinity of the galactic equator.

[1] Bauschinger, *V. J. S. Astr. Ges.* Jahrg. xxiv. p. 43.
[2] *Harvard Circular*, No. 82; *Astr. Nach.* No. 3965.

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Mr. Cleveland Abbe[1] sought to overcome the difficulty by imagining the nebulæ to be equably distributed over the surface of a "prolate ellipsoid," its longer axis coinciding approximately with the axis of the Milky Way; and this arrangement would undoubtedly give an appearance of crowding in the observed directions, since to an eye placed near the centre of such an oval figure, objects uniformly scattered over its surface would produce, by perspective, the effect of running together near its pointed ends. But this highly artificial contrivance was scarcely realisable. Our minds demand from a theory not barely that it "cover the phenomena," but also that it show itself congruous with the general plan of operations upon which we can see that nature works. Besides, the local distribution of nebulæ is so far from uniform, that antecedent probability is in favour of their general distribution being also marked by striking irregularities. The "canopy" of nebulæ in Virgo is then, we may rest assured, as genuine an accumulation in its own way as the spherical assemblage in the Magellanic Cloud.

But if there be no systematic difference of distance between the nebular classes occupying contrasted situations as regards the lines of galactic structure, there must be a systematic difference of constitution.[2] The parts of those objects crowding towards the poles must be comparatively small and close together. We have indeed already found reason to believe that clusters do, in point of fact, merge insensibly into nebulæ —that groups of genuine suns at wide intervals stand at the summit of an unbroken gradation of systems with smaller and closer constituents, down to accumulations of what is almost literally "star-dust." Resolvability is hence a question of constitution quite as much as of distance, and we are brought to the conclusion that, while galactic nebulæ are of what we may roughly describe as stellar composition, non-galactic nebulæ are more or less pulverulent. We cannot of course pretend to account for this remarkable distinction. All that can be said is that it *appears* to be actually existent. The irresolvable "polar" nebulæ perhaps escaped influences powerful over the "equatorial" ones. Their

[1] *Monthly Notices*, vol. xxvii. p. 262.
[2] Proctor, *Monthly Notices*, vol. xxix. p. 342.

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development, at any rate, seems to have taken a different course.

The spectroscope informs us that nebulæ possess radial velocities of the same order as those of stars. And their apparent fixity to visual observation unquestionably results, in part from their extreme remoteness, in part from their evasiveness of accurate measurement. The singularities of nebular distribution afford besides indirect evidence of movement. "Streaminess," if it mean anything, implies that the bodies affected by it advance in common towards a common goal. Aggregation at the end of a stream prompts the conjecture that a motion of advance was at a certain point, by some supervening attraction, swayed into a motion of revolution. A hint as to the origin of the Magellanic Clouds may hence be derived. They represent in some sort vessels filled through long pipes from a vast reservoir. And since the pipes are still there, the flow may be conceived to be still in progress. Were it to cease, the connection of the nubeculæ with the main nebular body would eventually be interrupted, and their insulation would become complete.

The fidelity with which gaseous nebulæ and clusters adhere to the Milky Way as seen projected upon the sphere, warrants the inference that their distribution in space is of a similar character. It would be unreasonable to disconnect them from a formation of which they so closely follow the lines. We can scarcely err in supposing that they lie in general *within*, not behind, or in front of it. Thus, the globular clusters richly strewn over the branch of the Milky Way from Scorpio to Ophiuchus, but withdrawn from the conterminous dark rift, plainly belong to the cloud-like stellar masses, owing to the absence of which the fissure seems black, although densely stocked with stars to the tenth magnitude. Other compressed groups stand out from a curtain of apparently still more remote stars, representing possibly a divergent galactic ramification.

Such ramifications must in many cases be greatly foreshortened as viewed from our nearly central position; in some, they may appear only as brilliant knots upon the "trunk" of the Milky Way. Possibly, the double cluster in Perseus may partake of this optical character. It may be the termination of a branch spreading inward, and seen nearly end-on.

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. Like the Perseus clusters, the Orion nebula gives indications of greater proximity than the main galactic accumulation, to which it is nevertheless beyond doubt structurally related. For a winding nebulous extension from the Milky Way can be traced past *a* Orionis through the belt and sword, the bright stars marking which are demonstrably associated with the nebula. The inference then presents itself that the whole mixed system, or series of systems, is placed upon an obliquely directed offset from the galactic zone. Reasoning of the same kind may perhaps apply to the combined nebula and cluster M 8. It occurs as a premonitory outlier of the leading division of the fissured Milky Way, from which it lies a little apart; and it seemed to Sir John Herschel only an "intense exaggeration" of the stellar collections in its neighbourhood.[1]

Summarising our conclusions, we find the unity of the stellar and nebular systems to be fully ascertained. They are bound together by relations of agreement and contrast scarcely less visibly intimate than those severally connecting individual members of each order. The general plan of nebular distribution is into two vast assemblages, one on either side of the Milky Way; but while this is, comparatively speaking, avoided by the unresolved crowd, it is densely thronged with clusters and gaseous nebulæ. The conditions of aggregation within the zone may hence be inferred to differ from those prevailing outside it; but how and why they differ remains inscrutable. As to the distances of the nebulæ, we know nothing positive; they no doubt vary extensively; nor can either fineness of grain, or faintness of light (both of which may be inherent qualities) serve to distinguish between those nearest to, and those further away from us. We may, however, plausibly conjecture that the hoodlike accumulation of nebulæ in Coma Berenices is of the same approximate remoteness with the main galactic stream, and may thus be said to constitute the polar cap of a sphere equatorially girdled by the Milky Way.

[1] *Cape Results*, p. 387.

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CHAPTER XXVII

THE CONSTRUCTION OF THE HEAVENS

SIR WILLIAM HERSCHEL conceived it to be the supreme object of astronomy "to obtain a knowledge of the construction of the heavens"; and this, in his view, would be accomplished by the "determination of the real place of every celestial body in space."[1] Thus limited, the problem would be completely solved could the absolute distance be ascertained of all the objects telescopically or photographically discernible in the sky. But even the attainment of this unattainable point would never have satisfied Herschel's restless spirit. The real scope of his inquiries went far beyond it. They had an historical as well as a statistical aim. "Looking before and after," they embraced the past and future, no less than the present of the Cosmos.

Modern investigators are of the same mind. The heavens are regarded by them from a *physiological*, rather than from a purely *anatomical* point of view. Mere knowledge of structure, however accurate, will not content them. The vital functions of the organism, the mutual dependence of its parts, the balance of the internal forces tending towards destruction and preservation, the dimly-apprehended aim of its divinely-sustained activity, engage their eager attention. The heavens live and move, and the laws of their life and motion involve the material destiny of man. It is impossible that he should be indifferent to them.

Even, however, if our instinctive interest in the working of the machine were less keen, we should be driven to search out the dynamical relations of its parts by the impossibility of

[1] *Phil. Trans.* vol. cvii. p. 302.

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otherwise arriving at a true knowledge of their egometrical relations. Not only are these variable from one moment to another, but acquaintance with them at any single moment is not conceivably accessible to us apart from previous acquaintance with modes and laws of motion. For our view of sidereal objects is not simultaneous. Communication with them by means of light takes time, and post-dates the sensible impressions by which we are informed of their whereabouts, in the direct proportion of their distances. We see the stars not where they are—not even where they were—at any one instant, but where they were on a sliding scale of instants. The epoch corresponding to the apparent position of each is different, and the range of difference extends over some thousands of years. The reduction of those positions to a common epoch so as to get a survey of the genuinely contemporary relations in space of all sidereal objects—ideally feasible at best—could not so much as be thought of as possible without a preliminary knowledge of their displacements during the centuries, or millenniums elapsed since the ethereal vibrations they originate started on their several journeys hither. Thus the study of configurations blends with the study of movements and forces; the restrictions placed upon thought by the effort to exclude all but a single aspect of phenomena fall away of themselves, and we are confronted, whether we will or no, by the stupendous problem of the universe as a vital whole.

As a whole; but not necessarily as the whole. The sidereal world presents us, to all appearance, with a finite system. Human reason would, indeed, otherwise be totally incompetent to deal with the subject of its organisation. There would be nothing for it but to lay down the arms of our understanding before its transcendental and appalling magnitude. But the probability amounts almost to certainty that star-strewn space is of measurable dimensions. For from innumerable stars, a limitless sum-total of radiations should be derived, by which darkness would be banished from our skies; and the "intense inane," glowing with the mingled beams of suns individually indistinguishable, would bewilder our feeble senses with its monotonous splendour. This laying bare, so to speak, of the empyrean would be the simple and

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certain result of the continuance *ad infinitum* of any arrangement of sidereal objects comparable with that prevailing in our neighbourhood. Unless, that is to say, light suffer some degree of enfeeblement in space. If this be the case, then our reasonings are put to silence, and a veil is drawn impenetrable to scrutiny. But there is not a particle of evidence that any such toll is exacted; contrary indications are strong; and the assertion that its payment is inevitable depends upon analogies which may be wholly visionary.[1] Ethereal absorption and the actual interception of stellar radiance by opaque masses are equally the creation of the speculative intellect. Neither mode of action is vouched for by experience. We are then, for the present, entitled to disregard the problematical effect of a more than dubious cause. The sidereal system cannot be regarded as in any true sense infinite. The scale of its construction, it is true, strikes imagination impotent; in the multitudinous splendour of its components, in the number and variety of the subordinate groups constituted by them, in the magnificent play of forces it unfolds, in the dim processes of development it suggests, it bears glorious witness to the power and wisdom of the Almighty Designer; yet it has limits, and for that reason it is a fit subject for the exercise of limited understandings. With further systems, "pinnacled deep" out of our sight for ever, we have, properly speaking, no scientific concern; we only know that "when a man hath done, then shall he begin" to declare the wonderful works of God.

Regarding the visible world of stars and nebulæ as an isolated, though excessively complex system, we may try to give the best order we can to our ideas respecting its constitution. Let us see what are the available data. The number of stars actually registered, including those in the Cape Photographic Durchmusterung, approaches a million, of which three-fifths, or thereabouts, are of magnitudes between the ninth and tenth, and the rest are brighter. Beyond the limits of this great census, minute stars abound; but to how many millions they would sum up if completely enumerated, can only be guessed very much *ad libitum*. Sir John Herschel estimated at five and a half millions the stars (to the

[1] Hirn, *Constitution de l'Espace Céleste*, p. 297.

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fourteenth photometric magnitude) perceptible over the entire sky with his twenty-foot reflector; Struve calculated them at twenty millions; and it has been vaguely surmised that a hundred millions could be shown by the most powerful modern telescopes. The photographic International Chart should contain, by M. Loewy's reckoning in 1900, thirty million stars to the fourteenth magnitude. Yet from the basis of the work done in preparing it at Greenwich down to 1904, the number was evaluated at only 13,880,000. Thus, we are still in great measure ignorant on the point. Different parts of the sky vary extremely in richness. In some, telescopic stars literally swarm; in others, they occur but scantily. It has been computed by Mr. Gore,[1] that if the whole heavens were as thickly strewn as the region of the Pleiades, the number of stars to the seventeenth (nominal) magnitude, would be about thirty-three millions. But the method of distribution within a definite cluster evidently gives no clue to that prevailing outside it. A fair specimen-field is, indeed, all but impossible to choose. Counts in the Milky Way, extended in the same proportion over the sphere, would vastly exaggerate the crowding of the stars; which would, in an equal degree, be underrated by counts executed outside it.

Reliable data on the subject might, one would have thought, be collected with practical usefulness by the method of "photographic star-gauging." Reckonings of the stars in their light-ranks, upon plates exposed for various lengths of time, ought to tell with certainty how far the ideal law of augmenting numbers holds good, and where "thinning-out" becomes apparent. In an equable stratum the stars must nearly quadruple at each descent of a magnitude, simply because the cubical space holding them is quadrupled.[2] Should this rule be overthrown by excess, a real crowding is indicated, *at the distance corresponding to the altered rate of increase;* if by defect, then obviously the supply of stars in the region examined is becoming exhausted, their scattering is sparser than in our nearer vicinity, and the termination of the series is at hand, if not already reached. Photographic soundings

[1] *Journ. Liv. Astr. Soc.* vol. vii. p. 180.

[2] For some reason still unexplained, the observed ratio falls consistently short of the theoretical ratio.

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have, nevertheless, some special drawbacks.[1] Their use is, above all, hampered by wide disparities depending on subtle variations in atmospheric transparency, which incalculably modify, from one night to the next, the registering powers of perfectly similar plates.

But even Herschel's Milky Way gauges, although indiscriminate as regards magnitude, afforded distinct evidence of a terminating series in the fact that the numbers of stars recorded by him amounted to only one-third of what might

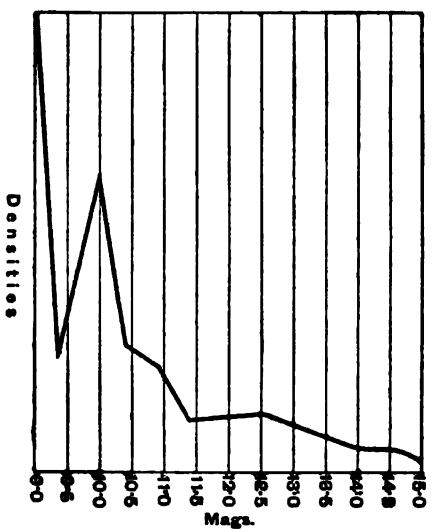

FIG. 88.—Distribution of 984 stars within 1° of the Pole, showing the ratio of numbers to space for each half-magnitude.

have been anticipated from the penetrating power of his instrument applied to an indefinitely extended system. And for a "mean sounding," at the northern galactic pole, M. Celoria, with a refractor showing, at the utmost, eleventh-magnitude stars, obtained a number almost identical with that given by Herschel's great reflector. The larger instrument then here revealed no additional stars. Similar symptoms of exhaustion in the star-supplies may be found in Professor Pickering's photographic catalogue of 947 stars within one degree of the celestial north pole.[2] A single glance at the

[1] Gavin J. Burns, *Journ. Brit. Astr. Ass.* vol. xii. p. 75.
[2] *Harvard Annals*, vol. xviii. p. 202.

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synoptical table giving the numbers for each half-magnitude, suffices to show that the numerical representation of the lower ranks is inadequate. The small stars are overwhelmingly too few for the space they must occupy if of average brightness; and they are too few in a constantly increasing ratio. The accompanying diagram (Fig. 38) represents graphically the decrease outward of density (or the proportion of numbers to space), deducible from Professor Pickering's enumeration on the sole supposition of the equal average lustre of each class of stars. Those of the ninth are the most thickly strewn; the intervals between star and star widen rapidly and continuously (for the sudden dip at 9·5 magnitude is evidently accidental) down to 11·5 magnitude, when a slight recovery, lasting to the thirteenth magnitude, sets in. A result of a different character was obtained by Professor Newcomb from a count of 312 stars to the eleventh magnitude on plates taken at Potsdam for the International Catalogue. Although the region examined lay close to the galactic pole, he could detect no manifest falling-off in the proportionate increase of number with faintness.[1] But until more comprehensive surveys of the same kind have been executed, it will be impossible to lay down any general rule for the thinning-out of sidereal strata. Nor, even if it were successfully formulated for the rest of the sky, could it apply to the Milky Way, where, "with both hands full," veritable star-dust is scattered.

A far-reaching influence is exercised by this great zone of condensation over the scattering of the stars, taken in the gross; but it grows more marked with their diminishing brightness. Seeliger's ascription to it of inferior efficacy in the southern hemisphere[2] may now be tested with the help of the Cape Durchmusterung. The preference of lucid stars for the Milky Way is slight yet unequivocal; it appears from some careful statistics published by Mr. Gore,[3] that even in them, the galactic zone is once and a half times richer than other parts of the sky. There is some evidence, however, that this crowding is towards a plane of condensation distinct from, though very close to that of the galaxy.

[1] *The Stars*, p. 284. [2] *Sitzungsberichte*, Munich, 1884, p. 521; 1886, p. 220.
[3] *Journ. Liv. Astr. Soc.* vol. vii. pp. 175, 182.

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A girdle of large stars spanning the southern hemisphere was thought by Sir John Herschel to be the projection of "a subordinate sheet, or stratum, deviating some twenty degrees from parallelism to the Milky Way."[1] The hint was further developed by Dr. Gould. "Few celestial phenomena" he considered to be "more palpable than the existence of a stream or belt of bright stars," traceable "with tolerable distinctness through the entire circuit of the heavens, and forming a great circle as well defined as that of the galaxy itself,"[2] which it crosses at an angle of about 20° in Crux and Cassiopeia. Traversing in the southern hemisphere Orion, Canis Major, Argo, the Centaur, Lupus, and Scorpio, it pursues its way in the northern through Taurus, Perseus, Cassiopeia, Cepheus, Cygnus, and Lyra, its line being less obviously continued by the stars of Hercules and Ophiuchus.[3] Like the Milky Way it seems to bifurcate near α Centauri, the branch there thrown off reuniting with the parent stem in Andromeda. That the stars thus marked out, to the number of about five hundred, constitute with the sun a cluster "of a flattened and somewhat bifid form," "distinct from the vast organisation of the Milky Way," grew into a conviction with the progress of Dr. Gould's observations.

The grounds upon which it was based have, nevertheless, been gradually undermined by close and varied research. Gould's star-belt continues to subsist; its reality is unquestioned; but its relations are different from those which he assigned to it. It has assuredly galactic, not solar proclivities. Mr. J. R. Sutton pointed out in 1891 that the tracts where it coalesces with the Milky Way are marked by profound disturbance of the nebulous stream.[4] But this could only result from an actual intermingling of the two formations. Again, many, perhaps most of the belt-stars give spectra of the helium type; and the chosen habitat of helium stars is—we are led to believe—within the galactic aggregations. Nor is there the least justification for holding the sun to be a member of any specialised stellar group. Some ostensible evidence derived from proper motions, implying the genuine existence

[1] *Cape Results*, p. 385.
[2] *Amer. Journ. of Science*, vol. viii. p. 333 (1874).
[3] *Uran. Argentina*, p. 355.
[4] *Knowledge*, vol. xiv. p. 124.

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of a solar cluster, is now known to have been misleading. Professor Kapteyn was justified, by the data placed at his disposal, in concluding that stars of the solar type are crowded in the neighbourhood of our sun,[1] but he fully recognised later the defective nature of those data, and withdrew the inference founded on them.[2]

The wide separation of the belt-stars from our own place in the universe adds incalculably to the importance of the phenomenon which they constitute. Their remoteness necessarily enhances our estimate of their size and luminosity; the condensation of an extraneous stellar multitude towards the plane they affect testifies to their attractive power; while their orderly arrangement, as if in a ring-like enclosure, still further perplexes the enigma presented by this surprising feature of the sidereal system. Its natural effect in disarranging the theoretical progression of photometric ranks augments seriously the difficulty of searching out the laws of stellar distribution. Into those ranks close upon five hundred extra stars are intruded, all above the seventh magnitude, which have no proper status among the denizens of intragalactic space. There is accordingly an excess of bright stars with small proper motions—sentinel-stars, one might call them, posted at the outskirts of the world, which might well serve to arrest runaways on the verge of breaking bounds through over-acceleration. Gould, in fact, showed that, deduction having been made of five hundred belt-stars, the remainder of those he had the means of enumerating, down to $9\frac{1}{2}$ magnitude, form a tolerably regular series, increasing in numbers nearly in the theoretical proportion of their diminishing light.[3] And the conclusion that these five hundred superfluous objects do in fact compose a group apart, is strengthened by the symmetrical arrangement, with regard to the "belt," of the bright stars outside it. Their tendency to collect towards its central plane was thought by Dr. Gould to be irrespective of the Milky Way, except in so

[1] *Proc. Amsterdam Acad. of Sciences*, April 29, 1892; January 28, 1893.

[2] *Ibid.* April 20, 1901, p. 689.

[3] The "empirical ratio" (that resulting from actual enumeration) of multiplication of numbers per magnitude, is 3·912; the theoretical ratio is 3·987.—*Uran. Argentina*, p. 367.

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far as the two formations coincide by the projection of one upon the other.

It is worth notice, too, that the present direction of the solar movement agrees with the general "lie" of the belt; although other stars give no sign of preference for any fundamental plane of revolution. Yet, quite obviously, the configuration of moving bodies is the aggregate expression of their mode of movement. A ring of stars can be a substantial reality only if it be constructed on a dynamical foundation. Its members must travel along the zone of their distribution. Should they eventually be proved not to do so, then Gould's belt will stand revealed as an illusory appearance. This question of systematic proper motions is evidently fundamental to the architectonics of the universe, and we are still a long way from being able to answer it.

In a long series of researches, Mr. Maxwell Hall of Jamaica, attempted to fix the elements of the sidereal system, regarded as an undivided whole.[1] The plan of structure attributed to it was identical with that suggested as barely possible to be realised in globular clusters. Nothing could be simpler. There being no dominant central mass, attractive force and velocity increase progressively outward, and all the movements in the collection, in whatever plane pursued, and whether in orbits nearly circular or highly eccentric, are governed by a single period, or *annus magnus*. But the scheme is practically unworkable as failing to accommodate itself to the irregularities and versatilities of nature; and its elaboration conveyed only a warning that the great problem was, by such means, impregnable.

The subject is one which, for the present, can only be approached tentatively; it would be highly undesirable that investigators should, for that reason, be discouraged from approaching it at all. The life of a science is in the thought that binds together its facts; decadence has already set in when they come to be regarded as an end in themselves. "Man is the interpreter of nature;" to draw up an inventory,

[1] *Memoirs R. Astr. Society*, vol. xliii. p. 157; *Monthly Notices*, vol. xxxix. p. 126; xlvii. p. 521; lvii. p. 357; lviii. p. 473. In the concluding papers of the series, Mr. Hall found it advisable to substitute for a law of force varying directly as the distance one constant at all distances from the centre.

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however, is not to interpret. It is true that speculation is prone to wander into devious ways; but then "truth emerges more easily from error than from confusion." And in sidereal science especially, there is danger lest investigators, seduced by the wonderful facilities of novel methods, should exhaust their energies upon the accumulation of data, and leave none for the higher work of marshalling them along the expanding lines of adequate theory. Mr. Hall's efforts had thus a value not to be measured by definite achievement.

It is scarcely probable that indications as to the general plan of the sidereal world sufficiently definite for purposes of numerical calculation, can be gathered during the present era of human knowledge. A limitless field of fruitful research, however, lies open even now in the systems of various degrees of subordination, the federated combination of which we may reasonably suppose to constitute the supreme unity of the cosmos. From double, triple, multiple groupings to knots, drifts, clusters, clouds of stars, an ascending scale of complex arrangement leads upwards to the unknown—perhaps beyond it to the unknowable.

As the outcome of recent statistical inquiries, a distinction has been set up between the stars arrayed into more or less definite groups or masses, and the apparently incoherent multitude forming the ordinary population of sidereal space. Every cluster is strewn with interjacent stars, and projected upon a background of disconnected stars. Even the great galactic drifts are not only seen through a starry veil, but may possibly (Professor Newcomb thinks) have a starry curtain drawn behind them.

Hence Newcomb's inference that, if we could remove from the sky the swarms of stars constituting the cloud-forms of the Milky Way, as well as all local aggregations, "we should have left a scattered collection, constantly increasing in density towards the galactic belt."[1] Sweeping away the crystallisation-products (to put it figuratively), we should find remaining a saturated solution of stars.

Again, Professor Pickering states that stellar distribution within and outside the Milky Way is so far identical, that the proportion of stars of a given magnitude to the total number

[1] *The Stars*, p. 276.

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in any single region is everywhere the same. But within the galactic area the numbers are doubled. There are twice as many stars of each consecutive photometric rank down to the twelfth magnitude. "The Milky Way," he adds, "covers about a third of the sky, and contains about half the stars. There is no evidence of a limit to the faintness of stars, although the proportionate increase in numbers becomes less for each successive magnitude."[1]

These are remarkable facts; and they acquire a deeper meaning from their association with physical diversities. The various spectral classes are not alike in their mode of scattering. Each obeys laws and tendencies proper to itself. Thus, Sirian stars, which form the majority of the entire, are drawn towards the plane of the Milky Way, and supply the material of its lucent throngs. Solar and Antarian stars, on the other hand, display no galactic preferences; they occur with equal profusion in all sections of the sphere. "The Universe is thus shown," Professor Pickering writes,[2] "to consist of two portions; first, the stars of the first type which, although frequent in all parts of the sky, predominate along a certain plane, thus forming the Milky Way. The second portion consists of stars whose spectra are of the second and third types. They show no concentration in the Milky Way, but are, in general, uniformly distributed in all parts of the sky. These two portions should be treated separately in all discussions of the structure of the Universe, such as studies of proper motion, parallax, motion of the Sun in space, etc. The proportion of stars of the first type to the total number increases when fainter stars are included, while with the Orion stars the opposite seems to be the case."

Our own sun, so far as present knowledge acquaints us, belongs to the class of what Herschel called "intersystematical stars"—stars, that is, exempt from particular ties, and exhibiting in their movements the net result of cosmical compulsion. How many of them there may be, we have no means of judging; but it is easily seen that special association becomes more prevalent with increasing remoteness from our post of observation. For this, among other reasons,

[1] *Harvard Annals*, vol. xlviii. p. 185. [2] *Ibid.* vol. lvi. p. 26.

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displacements among the members of the several groups evade notice. When their nature develops, as it must with the efflux of time, it will perhaps occasion embarrassment. The subsistence of a dynamical equilibrium may not always be implied by it. Companionship, which on the sidereal time-scale might be called transient, is even conceivable. One set of combinations may be dissolved to give place to others; a single star may pass from one vast confederacy to the next, seeking its fortune, as it were, through space; or, breaking away from the entire congeries of systems, rush out into the ethereal desert, to find itself, after milliards of ages, within the precincts of a strange galaxy beyond terrestrial ken with telescope or camera.

The more attentively the configuration of the stars is studied, the more clearly do special phenomena of grouping come into view. Among the minute stars of the Milky Way, above all, a tendency towards the display of typical patterns is, in certain parts of the sky, almost as unmistakable as it would be in a ball-room crowded with dancers suddenly arrested in threading their way through the figures of a quadrille or a minuet. Yet in the heavens, methodical distribution must always be to some extent masked by the projection upon the same surface of objects at totally different distances. That, under these circumstances, it should often be effaced is less remarkable than that it should occasionally become apparent.

One of the "typical forms" in which stars seem to collect, is that of an ellipse, or circle seen in perspective.[1] Radiated structures also occur; and Father Secchi, who early drew attention to this curious subject, regarded the presence of a large red star in a commanding situation among minor objects, as a common trait of physical arrangements.[2] The spectral relations of the objects composing them was made the subject of a suggestive study by J. Maclair Boraston in 1893.[3] As specimens of a class of objects to which the "persevering student" could make large additions "with an increasing conviction as to the mutual interdependence" of their constituents, Webb

[1] *Century Magazine*, Sept. 1889, p. 787.
[2] *Atti dell' Accad. Pont.* t. vii. p. 67.
[3] *Astr. and Astrophysics*, vol. xii. p. 68.

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singled out in the constellation Hercules, a "wreath," a "double chain," and a "recurved line of small stars proceeding from one of 7·5 magnitude."[1] The predominance of the "spray" form of association was dwelt upon by Proctor; while some regions, Professor Holden tells us, are characterised by streams of stars, defiling in rows of a dozen or two, across the telescopic field. "Others," he continues, "are rich in small definite ellipses of stars, often all of the same size. In some cases, stars are surrounded by circles of other fainter stars. In other instances, the ellipses become tolerably regular ovals, often of large size. These interlace in the most intricate manner. . . . We can frequently trace new and highly interesting features of the kind by paying attention to stars of one magnitude only. If we regard the eleventh-magnitude stars alone, for example, we may find rings and ovals of these stars forming a regular pattern in the sky. Interlacing with these may be found another pattern of similar ovals (usually smaller) of stars of the twelfth magnitude, and so on."[2]

It must, indeed, be admitted that the search for "star-patterns" is over somewhat treacherous ground. Imagination may here easily play the part of will-o'-the-wisp. Among a multitude of scattered objects, counterfeit groupings of any given design can be put together by a very slight stretch of fancy. It was shown experimentally by Lady Huggins that the random distribution of dots of Indian ink does not exclude the possibility, to a predisposed eye, of forming them into almost any desired figures. But the illustration should not, nor was it designed to lead us to set down as purely imaginary the visible peculiarities of stellar arrangement. This would be an extreme quite as mischievous as that of unqualified credulity, since there is cumulative evidence that the peculiarities in question are, in many cases, real and significant.[3]

Mr. Proctor expressed his conviction that "star streams" will eventually prove themselves genuine by the unanimity of

[1] *Cel. Objects*, p. 323.

[2] *Monthly Notices*, vol. l. p. 62. Cf. Barnard, *ibid.* p. 314; Backhouse, *ibid.* p. 374.

[3] *Publications West Hendon Observatory*, vols. i. ii.

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their proper motions.[1] And it is obvious that they can only subsist upon this condition. Their order would otherwise be a merely passing coincidence. Stars marching "in Indian file," are presumably swayed by an identical force acting upon them from a very great distance. The group that they form is not self-centred, but makes only a part of a larger organisation. Segregation, on the other hand, is the distinguishing "note" of true clusters. They might be described as autonomous democracies, each of their members obeying the united commands of all, while outside influences, although exerted upon them collectively, are without effect upon their internal regimen.

A "streaming" can then be discriminated (at least ideally) from a "clustering" collection of stars, by the circumstance that the centre of movement of the one is external, of the other internal. It may possibly be found that the two plans of organisation prevail respectively in different sections of the Milky Way; there is some appearance that they not unfrequently compete or combine within the same cluster, the streaming tendency working towards the dissolution, the clustering tendency for the preservation of the system. This is not the only feature of sidereal construction which conveys a hint to us that the world of stars and nebulæ is in a state of transition. We see it in only one phase of its long development. To regard its condition as settled upon an unalterable basis, would be to misconstrue signs everywhere legible to attentive scrutiny.

Since stars and nebulæ are undeniably united into a single scheme, our view of the universe must embrace both classes. The distribution of nebulæ is in fact complementary to the distribution of stars. Assemblages of the one kind fill in the outlines left blank by the assemblages of the other. The Milky Way, so far as can be immediately discerned, is a rifted and irregular ring, furnished with innumerable tentacular appendages, and composed of stars in every stage of aggregation. This ring, however, has obvious geometrical relations with the rest of the sidereal structure. It marks the equator of a vast globe, of which the poles are canopied by the nebulæ. Necessarily, too, of a rotating globe, since axial

[1] *Universe of Stars*, p. 84.

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movement alone gives rise to the distinction between poles and equator.

The opinion that the shape of the visible universe is spherical, or spheroidal, rather than lenticular, was expressed by Radau,[1] Klein, and Falb.[2] The polar relations of the nebulæ to the plane of the Milky Way admit indeed of no other interpretation. And these relations can scarcely have been determined otherwise than by the rotation on an axis of the colossal, undivided volume. The condition thus indicated as primitively existing may have become modified with time; and, even if still prevalent, should be unrecognisable by us, since the relative situations of the heavenly bodies would, as Falb remarked, be absolutely unaffected by it.

All that we can see clearly is that an universal movement of rotation had much to do with the present distribution of matter in sidereal space. Whether the forces which have brought it about are still active, must remain an open question. The opposite tendencies of stars to gather in the equatorial plane, and of nebulæ to stream towards the poles of the system, may not even yet be exhausted; but the decision of this point must be left to a dim futurity. The efficacy, in the past or at present, of contrary drifts would apparently imply an inherent difference in the qualities of the objects respectively swayed by them; and would, so far, contribute to invalidate the consecrated hypothesis of stellar development from nebulæ.

We can, indeed, hesitate to admit neither the fundamental identity of the material elements of the universe, nor the nebulous origin of stars. The transition from one to the other of the two great families of the sidereal kingdom is so gradual as to afford a rational conviction that what we see contemporaneously in different objects has been exhibited successively by the same objects. Planetary nebulæ pass into gaseous stars on one side, into nebulous stars on the other; the greater nebulæ into clusters. The present state of the Pleiades refers us inevitably to an antecedent condition closely resembling that of the Orion nebula; the Andromeda nebula

[1] *Bull. Astr.* t. ii. p. 88.

[2] *Handbuch der Himmelserscheinungen*, Th. ii. p. 312; *Sirius*, Bände vii. p. 10, viii. p. 198.

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may represent the nascent stage of a splendid collection of suns. But even though stars without exception have sprung from nebulæ, it does not follow that nebulæ without exception grow into stars. The requisite conditions need not invariably subsist. Other ends than that of star production are perhaps met and promoted by the chief part of the present nebulous contents of the heavens. The contrast between stellar and nebular distribution is intelligible only as expressing a definitive separation of the life-histories of the two classes—a divergence destined to be perpetual between their lines of growth.

Progress, then, is the law of the universe. From its present state we can obscurely argue a "has been" and a "shall be." The face of the skies is not cast in stereotype. "As a vesture Thou shalt change them, and they shall be changed." They shall change, by no caprice of hazard, but in subjection to laws unalterable in their essence although infinitely various in their applications, divinely directed towards the continually more perfect embodiment of the unfolding Eternal Thought.

But the glory of the heavenly bodies, it is asserted, must come to an end. It results from a merely transitory state of things. The radiations, by virtue of which they shine, are the outcome of what may be figuratively termed the effort of nature to establish a universal thermal equilibrium. This condition will be attained when the frigid "temperature of space" reigns in all the millions of bodies which once were suns, and will thenceforward revolve, amid "darkness that may be felt," the mechanism of their movements unimpaired, but inert, lifeless, and invisible. Is this then the predestined end? Science replies in the affirmative. That is to say, it knows no better. Yet there is much as to which it is ignorant. Matter rests upon a subsensible basis, into the arcana of which no inquiry has penetrated. The observation of phenomena leads, it may be said, to the shore of an all-diffusive ocean of force, the existence of which is implicated in their occurrence. That is all we know; at the brink of the ocean we pause, helpless to sound its depths, or number the modes of its manifestations, or predict the tasks of renovation or preservation committed to it. We can only

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recognise with supreme conviction that He who made the heavens can restore them, and that when the former things have passed away, and the scroll of the skies is taken out of sight, "like a book folded up," a "new heaven and a new earth" shall meet the purified gaze of recreated man.

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APPENDIX

TABLE I

The 40 Brightest Stars in order of Magnitude[1]

THE SUN. STELLAR MAGNITUDE −26·5

Designation.	R. A. 1900.	Dec. 1900.	Mag.	Spectrum.	Remarks.
	h. m.				
Sirius . .	6 40·7	−16° 35′	−1·58	Sirian .	Binary; satellite of 10m.
Canopus . .	6 21·8	−52° 39′	−0·86	Sirian-solar	Insensible parallax.
α Centauri .	14 32·8	−60° 25′	+0·06	Solar .	Components of 0·36m and 1·61m.
Vega . .	18 38·6	+38° 41′	0·14	Sirian .	
Capella . .	5 9·3	+45° 54′	0·21	Solar .	Spectroscopically compound.
Arcturus . .	14 11·1	+19° 42′	0·24	Solar .	
Rigel . .	5 9·7	− 8° 19′	0·34	Helium .	
Procyon . .	7 34·1	+ 5° 29′	0·48	Sirian-solar	Binary; satellite of 13m.
Achernar . .	1 34·0	−57° 44′	0·60	Helium .	Real brightness 28 times solar.
β Centauri .	13 56·8	−59° 53′	0·86	Helium .	
Altair . .	19 45·9	+ 8° 36′	0·89	Sirian .	Spectrum hazy.
Betelgeux .	5 49·8	+ 7° 23′	1·0 to 1·4	Antarian .	Irregularly variable.
α Crucis . .	12 21·0	−62° 33′	1·05	Helium .	Combines two equal stars.
Aldebaran .	4 30·2	+16° 19′	1·06	Solar .	
Pollux . .	7 39·2	+28° 16′	1·21	Solar .	
Spica . .	13 19·9	−10° 38′	1·21	Helium .	Spectroscopic binary.
Antares . .	16 23·8	−26° 13′	1·22	Antarian .	Companion gives a Sirian spectrum.
Fomalhaut .	22 52·1	−30° 9′	1·29	Sirian .	
α Cygni . .	20 38·0	+44° 55′	1·33	Sirian .	Insensible parallax.
Regulus . .	10 3·0	+12° 27′	1·34	Helium .	
β Crucis . .	12 41·9	−59° 9′	1·50	Helium .	McClean's "oxygen star."
Castor . .	7 28·2	+32° 6′	1·58	Sirian .	Components 2·0m and 2·85m.
γ Crucis . .	12 25·6	−56° 33′	1·60	Antarian .	
e Canis Majoris	6 54·7	−28° 50′	1·63	Helium .	
ε Ursæ Majoris	12 49·6	+56° 30′	1·68	Sirian .	
Bellatrix . .	5 19·8	+ 6° 16′	1·70	Helium .	
λ Scorpii . .	17 26·8	−37° 2′	1·71	Helium .	
e Carinæ . .	8 20·5	−59° 11′	1·74	Solar .	Spectrum composite.
e Orionis . .	5 31·1	− 1° 16′	1·75	Helium .	
β Tauri . .	5 20·0	+28° 31′	1·78	Helium .	
β Carinæ . .	9 12·1	−69° 18′	1·80	Sirian .	
α Trianguli Australis	16 38·1	−68° 51′	1·88	Solar .	

[1] See *Harvard Annals*, vol. xlviii. No. 4.

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Designation.	R. A. 1900.	Dec. 1900.	Mag.	Spectrum.	Remarks.
	h. m.				
α Persei . .	3 17·2	+49° 30′	1·90	Solar .	
ζ Orionis . .	5 35·7	− 2° 0′	1·91	Helium .	Components of 2·0m and 4·2m.
η Ursæ Majoris	13 43·6	+49° 49′	1·91	Helium .	
γ Geminorum .	6 31·9	+16° 29′	1·93	Sirian .	Spectroscopic binary.
α Ursæ Majoris	10 57·6	+62° 17′	1·95	Solar .	
ε Sagittarii .	18 17·5	−34° 26′	1·95	Sirian .	
δ Canis Majoris	7 4·3	−26° 14′	1·98	Solar .	
β Canis Majoris	6 18·3	−17° 54′	1·99	Helium .	

TABLE II

Representative Variable Stars

1. LONG-PERIOD VARIABLES

Name.	R. A. 1900.	Dec. 1900.	Range in Mag.	Period in Days.	Remarks.
	h. m.				
Mira Ceti .	2 14·3	− 3° 26′	1·7- 9·5	332	Period subject to deviations of fully 20d from the mean. Rise occupies 125d.
U Orionis .	5 49·9	+20° 10′	5·8-12·3	375	Spectrum third type, with bright H-lines at maximum.
R Carinæ. .	9 29·7	−62° 21′	4·5-10	310	Roberts finds an inequality in the period comprised in about 33 years.
R Normæ .	15 28·8	−49° 10′	7 -11·5	471	Secondary maxima and minima observed by Innes.
χ Cygni . .	19 46·7	+32° 40′	4·5-13·5	406	Period slowly lengthening.
V Delphini .	20 43·2	+18° 58′	7·3-17·3	540	Range of magnitude the widest known.

2. IRREGULAR VARIABLES

S Doradûs .	5 18·9	−69° 21′	8·2- 9·8	...	In cluster N.G.C. 1910. Spectrum first type with bright H-lines.
η Carinæ . .	10 41·2	−59° 10′	−1·0-+7·7	...	At a constant minimum since 1886.
R Coronæ Borealis	15 44·4	+28° 28′	5·5-10·1	...	Sudden failures of light affect this star at uncertain intervals.
u Herculis .	17 13·6	+33° 12′	4·6- 5·4	...	Helium spectrum; diffuse lines. Radial velocity widely variable.
R Scuti . .	18 42·2	− 5° 49′	4·8- 7·8	...	Spectrum solar with bright lines. Radial velocity constant at +42 kms. per second.
RW Cygni .	20 25·2	+39° 39′	7·7-10·5	...	Spectrum probably variable; of fourth type in 1885 (Espin).

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3. CEPHEID VARIABLES

Name.	R. A. 1900.	Dec. 1900.	Range in Mag.	Period in Days.	Remarks.
	h. m.				
U Leporis .	4 52·0	−21° 22′	9·0-10·0	13·9	Rise very rapid. Period lengthening (Innes).
R Muscæ . .	12 36·0	−68° 52′	6·5- 7·6	0·8	Spectrum solar type.
W Sagittari .	17 58·6	−29° 35′	4·3- 5·1	7·6	Binary; revolution synchronous with light-change. Subsidiary period of 3·3d indicated (Curtiss).
η Aquilæ . .	19 47·4	+ 0° 45′	3·7- 4·5	7·1	Discovered by Pigott, 1784. Spectroscopic binary.
T Vulpeculæ .	20 47·2	+27° 52′	5·5- 6·5	4·4	Spectroscopic binary (Frost).
δ Cephei . .	22 25·4	+57° 54′	3·7- 4·6	5·3	Spectroscopic binary. Non-eclipsing. Spectrum solar type.

4. GEMINID VARIABLES

ζ Geminorum .	6 58·2	+20° 43′	3·8- 4·3	10·2	Non-eclipsing binary. Double periodicity indicated (Campbell).
V Puppis . .	7 55·4	−48° 58′	4·1- 4·8	1·4	Spectroscopic binary. Helium spectrum.
S Antliæ .	9 27·9	−28° 11′	6·3- 6·8	0·3	Sirian-solar spectrum.
W Ursæ Majoris	9 36·7	+56° 25′	7·9- 8·6	0·17	Light-curve nearly symmetrical (Müller and Kempf, 1903).
β Lyræ . .	18 46·4	+33° 15′	3·4- 4·1	12·9	Helium spectrum with variable bright lines. Double periodicity.
V Vulpeculæ .	20 32·3	+26° 15′	8·3- 9·7	75·7	Light-change analogous to that of β Lyræ.

5. CLUSTER VARIABLES

No. 8 ω Centauri	13 20·8	−46° 57′	12·8-14·3	0·52	One of 128 variable components of the great southern cluster. Nearly constant minimum of 6h duration.
No. 7 Messier 5	15 13·5	+ 2° 27′	13·5-14·9	0·50	Situated in the globular cluster in Libra. Minimum lasts 0·4 of total period.
S Aræ . .	17 51·5	−49° 25′	9·5-10·8	0·45	Rises to maximum in 1 h. 10 m.
Y Lyræ . .	18 34·2	+43° 52′	11·3-12·3	0·51	Increase of light effected in 1 h. 30 m.
14. 1904 Cygni	20 1·3	+58° 4′	10·7-11·6	0·13	Discovered by Madame Ceraski in 1904.
UY Cygni .	20 52·3	+30° 3′	9·6-10·4	0·5	Rise completed in 1 h. 58 m.

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TABLE III

List of Eclipsing Stars

Name of Star.	R. A. 1900.	Dec. 1900.	Period in Days.	Phase in Mag.	Remarks.
	h. m.				
U Cephei . .	0 53·4	+81° 20′	2·5	7·0- 9·2	Duration of phase =11 h. Eclipse annular (Yendell).
Z Persei . .	2 33·7	+41° 36′	3·1	9·4-12	Discovered by Williams, 1902.
Algol . .	3 1·7	+40° 34′	2·8	2·1- 3·2	Spectroscopically verified as an eclipsing variable by Vogel in 1889.
RT Persei .	3 16·7	+46° 12′	0·85	9·5-11·0	Phase occupies 2½ h. Discovered by Madame Ceraski in 1904.
λ Tauri . .	3 55·1	+12° 12′	3·9	3·3- 4·2	Phase lasts 10 h. Eclipsing star partially luminous.
R Canis Majoris	7 14·9	−16° 12′	1·1	5·7- 6·3	Phase completed in 5 h. Density cannot exceed 0·26 that of the sun (H. N. Russell).
Y Camelopardali	7 27·6	+76° 17′	3·3	9·5-11·2	Discovered by Madame Ceraski in 1900.
R^2 Puppis .	7 43·5	−41° 8′	6·4	10·0-11·0	Phase lasts 16 h. (Innes). Density of system $\frac{1}{4}$th solar (Roberts).
X Carinæ . .	8 29·1	−58° 53′	0·5	7·9- 8·7	Two bright stars, revolving in 1d·1, undergo alternate eclipses (Roberts).
S Cancri . .	8 38·2	+19° 24′	9·4	8·0-10·2	Duration of phase 21½ h. Density =0·025 solar (Russell).
S Velorum .	9 29·4	−44° 46′	5·9	7·8- 9·3	Phase occupies 15 h. Density =0·04 solar (Russell).
R^2 Velorum .	10 17·8	−41° 51′	1·8	10·0-10·9	Duration of phase =3 h. 20 m. Density =0·4 solar (Roberts).
Z Draconis .	11 39·8	+72° 49′	1·4	9·4-12·5	Phase accomplished in 6 h. 40 m. Discovered by Madame Ceraski in 1908.
δ Libræ . .	14 55·6	− 8° 7′	2·3	5·0- 6·2	Phase occupies 12 h. Radial velocity widely variable.
U Coronæ Borealis	15 14·1	+32° 1′	3·4	7·6- 8·7	Duration of phase =10 h. Period shortening. Density =0·1 solar (Russell).
R Aræ . .	16 31·4	−56° 48′	4·4	6·9- 8·0	Duration of phase =9 h. 30 m. (Roberts).
U Ophiuchi .	17 11·4	+ 1° 19′	0·8	6·0- 6·7	Phase occupies 5 h. 20 m. Period affected by an inequality cyclical in about 37 years (Chandler).
RV Ophiuchi .	17 29·8	+ 7° 19′	?	9·0-11·2	
Z Herculis .	17 53·6	+15° 9′	3·9	7·1- 7·9	Two unequal eclipses take place in each period, the principal lasting 6·6 h., the secondary 4 h. (Dunér).
RS Sagittarii .	18 11·0	−34° 8′	2·4	5·7- 6·3	Period unequally divided by a secondary minimum showing orbital eccentricity =0·25 (Roberts).

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Name of Star.	R. A. 1900.	Dec. 1900.	Period in Days.	Phase in Mag.	Remarks.
	h. m.				
V Serpentis .	18 11·1	−15° 33′	3·5	9·5-10·0	Period halved by a secondary minimum (Pickering).
RX Herculis .	18 26·0	+12° 32′	0·8	7·0- 7·5	Period comprises two unequal minima. Eclipsing character doubted by Yendell.
U Scuti . .	18 48·9	−12° 44′	0·95	9·1- 9·6	Duration of phase =5 h. Secondary minima indicated. Discovered by Ceraski in 1901.
RV Lyræ .	19 12·5	+32° 15′	3·5	11·0-12·8	Discovered by Williams, 1902.
U Sagittæ .	19 14·4	+19° 26′	3·3	6·5- 9·1	Phase occupies 12 h. Discovered by Schwab, 1901.
SY Cygni .	19 42·7	+32° 28′	6·0	10·0-12·1	Discovered by Madame Ceraski in 1900.
W² Cygni .	20 0·6	+41° 18′	3·3	9·3-12·5	Discovered by Madame Ceraski in 1904.
SW Cygni .	20 3·8	+46° 1′	4·5	9·0-11·7	Phase lasts 18 h. Discovered by Madame Ceraski in 1898.
VW Cygni .	20 11·4	+34° 12′	8·5	9·8-11·8	Phase lasts 19½ h. Discovered by Williams, 1903.
UW Cygni .	20 19·6	+42° 55′	3·4	10·0-12·0	Phase lasts 8½ h. Discovered by Williams, 1901.
W Delphini .	20 33·1	+17° 56′	4·8	9·4-12·1	Duration of phase =14 h. Discovered by Miss Wells, 1895.
Y Cygni . .	20 48·1	+34° 17′	1·4	7·1- 7·9	System probably composed of two mutually eclipsing equal stars revolving in twice the light-period (Dunér).
V² Cygni. .	21 2·3	+45° 28′	1·5	12·4-13·7	Discovered by Madame Ceraski, 1902.
UZ Cygni . .	21 55·2	+43° 52′	31·3	8·9-11·6	Phase lasts 2d. Discovered by Mrs. Fleming, 1902. Secondary minima observed by Hartwig.

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TABLE IV

List of Computed Binaries with measured Parallaxes

Name of Star.	Magnitudes of Components.	Period.	Mean Distance in Seconds of Arc.	Mean Distance in Radii of Earth's Orbit.	Parallax.	Mass of System. Solar mass = 1.	Remarks.
η Cassiopeiæ	4·0, 7·0	196 years (See)	8″·2	53·3	0″·154	4	Mass of primary = 2·9; of attendant = 1·1.
Algol . .	2·1, ?	2·8 days	?	?	0″·035	0·67	Density of the visible and invisible components assumed to be equal.
α_2 Eridani (close pair)	9·2, 10·9	180 years (Burnham)	6″·25	38	0″·166	1·64	The brighter star is slightly the less massive of the pair (Lewis).
Capella .	0·8, 1·5	104 days	?	?	0″·08	2·14 (Minimum value)	The mass is calculated on the assumption that the orbital plane coincides with the line of sight.
Sirius . .	−1·6, +10	50·4 years (Lohse)	7″·43	20	0″·37	3·184	The brilliant star possesses only about two-thirds of the joint mass, though more than 40,000 times more luminous than its satellite.
Castor . .	2·0, 2·85	347 years (Doberck)	5″·76	115	0″·05	12·66	The parallax, derived from spectroscopic measures, has only an experimental value.
Procyon .	0·5, 13	40 years (See)	5″·84	16	0″·325	2·6	Mass of satellite $\frac{1}{4}$th that of primary, which shines with five times the solar brilliancy, or 100,000 times that of its attendant star.
γ Virginis .	3·0, 3·2	194 years (See)	3″·99	54	0″·074	3·3	Components equally massive (Lewis). Each is nine times more luminous than the sun (Russell).
α Centauri .	0·4, 1·9	81 years (See)	17″·7	23·6	0″·75	2	Components approximately equal in mass.
70 Ophiuchi .	4·5, 6·0	88·4 years (Schur)	4″·55	28	0″·162	2·8	The fainter component possesses four-fifths the total mass (Prey).
δ Equulei .	4·5, 5·0	5·7 years (Hussey)	0″·28	4	0″·07	1·9	The parallax results from spectroscopic measures by Hussey.
85 Pegasi .	5·7, 11·3	24 years (See)	0″·89	16·6	0″·054	11·3	The satellite is $1\frac{3}{4}$ times more massive than the principal star, which eclipses its light (Comstock).

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TABLE V

List of Stars with sensible Parallaxes[1]

Name of Star.	R.A. 1900.	Dec. 1900.	Mag.	Parallax.	Authority.
	h. m.				
β Cassiopeiæ .	0 3·8	+58° 36′	2·4	0″·15	Pritchard. Photography.
Groombridge 34	0 12·7	+43° 27′	8·0	0″·29	Auwers. Differences of R.A.
ξ Toucani .	0 14·9	−65° 28′	4·3	0″·138	Elkin. Heliometer.
β Hydri . .	0 20·5	−77° 49′	2·9	0″·134	Gill. Heliometer.
α Cassiopeiæ .	0 34·8	+55° 59′	2·5	0″·04	Pritchard. Photography.
η Cassiopeiæ .	0 43·0	+57° 17′	3·6	0″·18	Peter. Heliometer.
μ Cassiopeiæ .	1 1·6	+54° 26′	5·2	0″·13	Peter. Heliometer.
Polaris . .	1 22·6	+88° 46′	2·1	0″·05	Pritchard. Photography.
Fomalhaut .	1 34·0	−57° 45′	0·6	0″·04	Gill. Heliometer.
τ Ceti . .	1 39·4	−16° 28′	3·6	0″·31	Flint. Differences of R.A.
e Eridani . .	3 15·9	−43° 27′	4·3	0″·15	Elkin. Heliometer.
o^2 Eridani .	4 10·7	+17° 48′	4·5	0″·166	Gill. Heliometer.
Aldebaran .	4 30·2	+16° 19′	1·1	0″·107	Elkin. Heliometer.
Z.C. 5^h 243 .	5 6·7	−45° 3′	8·5	0″·312	De Sitter. Heliometer.
Capella . .	5 9·3	+45° 54′	0·2	0″·08	Elkin. Heliometer.
Betelgeux .	5 49·8	+ 7° 23′	1·0±	0″·023	Elkin. Heliometer.
ψ^5 Aurigæ .	6 39·5	+43° 41′	5·3	0″·11	Schur. Micrometer.
Sirius . .	6 40·7	−16° 35′	−1·6	0″·37	Gill. Heliometer.
51 Hev. Cephei	6 53·7	+87° 12′	5·2	0″·027	Wagner. Meridian observations.
Castor . .	7 28·2	+32° 6′	1·6	0″·05	Curtiss. Spectroscopic measures.
Procyon . .	7 34·1	+ 5° 29′	0·5	0″·325	Elkin. Heliometer.
Pollux . .	7 39·2	+28° 16′	1·2	0″·056	Elkin. Heliometer.
Lalande 15290 .	7 47·2	+30° 53′	8·2	0″·02	Peter. Heliometer.
10 Ursæ Majoris	8 54·2	+42° 11′	4·1	0″·02	Wagner. Meridian observations.
Lalande 18115 .	9 7·6	+53° 7′	7·8	0″·18	Peter. Heliometer.
θ Ursæ Majoris	9 26·2	+52° 8′	3·3	0″·09	Peter. Heliometer.
Lalande 19022 .	9 37·1	+43° 10′	8·0	0″·06	Kapteyn. Differences of R.A.
20 Leonis Minoris	9 55·2	+32° 25′	5·5	0″·06	Kapteyn. Differences of R.A.
Regulus . .	10 3·0	+12° 27′	1·3	0″·022	Elkin. Heliometer.
Groombridge 1618 .	10 5·2	+49° 58′	6·8	0″·17	Peter. Heliometer.
Groombridge 1646 .	10 21·9	+49° 19′	6·5	0″·11	Kapteyn. Differences of R.A.
Groombridge 1657 .	10 27·7	+49° 42′	7·6	0″·048	Kapteyn. Differences of R.A.
Lalande 21185 .	10 57·9	+36° 38′	7·5	0″·344	H. N. Russell. Photographic measures.
Lalande 21258 .	11 0·5	+44° 2′	8·5	0″·24	Kapteyn, Auwers, and Krüger.
Σ 1516 . .	11 8·6	+74° 1′	7·0	0″·10	De Ball. Micrometer.

[1] In preparing this list recourse has been had to several authorities, especially to the similar collections published by Newcomb and Kapteyn, in *The Stars* and *Groningen Publications*, No. 8, respectively.

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Name of Star.	R.A. 1900.	Dec. 1900.	Mag.	Parallax.	Authority.
	h. m.				
A. Oe. 11677 .	11 14·8	+66° 23′	9·0	0″·10	Franz. Heliometer.
Bradley 1584 .	11 29·6	−32° 18′	6·0	0″·03	Flint. Differences of R.A.
Σ 1561 . .	11 33·5	+45° 40′	6·7	0″·04	Kapteyn. Differences of R.A.
Groombridge . 1822	11 40·3	+48° 14′	8·0	0″·03	Kapteyn. Differences of R.A.
Groombridge . 1830	11 47·2	+38° 26′	6·6	0″·148	Kapteyn and others.
Groombridge . 1855	12 4·6	+40° 49′	7·3	0″·07	Kapteyn. Differences of R.A.
α Crucis . .	12 21·0	−62° 33′	1·0	0″·05	Gill. Heliometer.
γ Virginis .	12 36·3	− 0° 55′	2·9	0″·074	H. N. Russell. Photography.
β Comæ . .	13 7·2	+28° 23′	4·5	0″·11	Peter. Heliometer.
β Centauri .	13 56·8	−59° 53′	0·9	0″·03	Gill. Heliometer.
Arcturus . .	14 11·1	+19° 42′	0·24	0″·024	Elkin. Heliometer.
α Centauri .	14 32·8	−60° 25′	0·06	0″·75	Gill. Heliometer.
Piazzi XIV. 212	14 51·5	−20° 58′	6·3	0″·167	De Sitter. Heliometer.
Lalande 27298 .	14 52·3	+54° 4′	7·5	0″·088	Peter. Heliometer.
Antares . .	16 23·3	−26° 13′	1·2	0″·021	Finlay. Heliometer.
η Herculis .	16 39·5	+39° 7′	3·6	0″·40	Wagner. Meridian circle.
δ Herculis .	17 10·9	+24° 57′	3·2	0″·05	Leavenworth. Micrometer.
π Herculis .	17 11·6	+36° 55′	3·4	0″·11	Wagner. Meridian circle.
ν′ Draconis .	17 30·2	+55° 15′	4·9	0″·32	Wagner. Meridian circle.
A. Oe. 17415 .	17 37·0	+68° 26′	9·0	0″·25	Krüger. Heliometer.
70 Ophiuchi .	18 0·4	+ 2° 31′	4·2	0″·158	Krüger. Heliometer.
Vega . .	18 33·6	+38° 41′	0·14	0″·082	Elkin. Heliometer.
Σ 2398 . .	18 41·7	+59° 29′	8·2	0″·35	Lamp. Differences of declination.
31 Aquilæ .	19 20·2	+11° 44′	5·3	0″·068	Peter. Heliometer.
σ Draconis .	19 32·6	+69° 29′	4·8	0″·175	Peter. Heliometer.
Altair . .	19 45·9	+ 8° 36′	0·9	0″·231	Elkin. Heliometer.
61 Cygni . .	21 2·4	+38° 15′	6·1	0″·37	Mean of photographic measures.
δ Equulei .	21 9·6	+ 9° 36′	4·7	0″·07	Hussey. Spectroscopic.
ε Indi . .	21 55·7	−57° 12′	4·8	0″·278	Gill and Elkin. Heliometer.
α Gruis . .	22 1·9	−47° 27′	2·2	0″·015	Gill. Heliometer.
Krüger 60 .	22 24·5	+57° 12′	9·0	0″·278	Schlesinger. Photographic measures.
Fomalhaut .	22 52·1	−30° 9′	1·3	0″·130	Gill. Heliometer.
Lacaille 9352 .	22 59·4	−36° 26′	7·1	0″·283	Gill. Heliometer.
Bradley 3077 .	23 8·5	+56° 37′	6·0	0″·138	Peter. Heliometer.
85 Pegasi. .	23 57·0	+26° 33′	5·8	0″·054	Brünnow. Micrometer.

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TABLE VI

List of Stars with Proper Motions of 1″·9 and Upwards

Name of Star.	R.A. 1900.	Dec. 1900.	Mag.	Annual Motion.	Remarks.
	h. m.				
Z.C. 5h 243	5 7·7	−45° 8′	8·5	8″·7	Discovered by Kapteyn and Innes from C.P.D. plates.
Groombridge 1830	11 47·2	+38° 26′	6·5	7″·0	Argelander's "flying star."
Lacaille 9352	22 59·4	−36° 26′	7·1	7″·0	Distance = 11½ light-years.
Cordoba 32416	23 59·5	−37° 26′	8·2	6″·2	"Gould's star" in Sculptor.
61 Cygni	21 2·4	+38° 15′	6·1	5″·2	Components 21″ apart.
Lalande 21185	10 57·9	+36° 38′	8·5	4″·8	
ε Indi	21 55·7	−57° 12′	4·8	4″·7	
Lalande 21258	11 0·5	+44° 2′	8·5	4″·4	
o_2 Eridani	4 10·7	− 7° 48′	4·7	4″·1	Chief of a triple system.
μ Cassiopeiæ	1 1·6	+54° 26′	5·4	3″·8	
α Centauri	14 32·8	−60° 25′	0·6	3″·7	Components 22″ apart.
A. Oe. 14318	15 4·7	−15° 59′	9·3	3″·6	Stars 5′ apart.
A. Oe. 14320	15 4·7	−15° 54′	9·2	3″·6	Identical motion.
Lacaille 8760	21 11·4	−39° 15′	6·8	3″·4	
ε Eridani	3 15·9	−43° 27′	4·4	3″·1	
A. Oe. 11677	11 14·8	+66° 23′	9·0	3″·0	
ε Eridani	3 28·2	− 9° 48′	3·8	3″·0	
Groombridge 34	0 12·7	+43° 27′	7·9	2″·8	Double at 40″ interval.
Piazzi II. 123	2 30·6	+ 6° 25′	6·0	2″·4	
Lalande 25372	13 40·7	+15° 26′	8·5	2″·3	
Arcturus	14 11·1	+19° 42′	0·2	2″·3	
Σ 2398	18 41·7	+59° 29′	8·2	2″·3	Components 16″ apart.
β Hydri	0 20·5	−65° 28′	2·7	2″·2	
Lalande 7448	3 56·5	+35° 2′	8·5	2″·2	
Weisse V. 592	5 26·4	− 3° 42′	9·0	2″·2	
Bradley 3077	23 8·5	+56° 37′	6·0	2″·1	
ζ Tucanæ	0 14·9	−65° 28′	4·1	2″·0	
Lalande 15290	7 47·2	+30° 55′	8·2	2″·0	
Piazzi XIV. 212	14 51·6	−20° 58′	6·0	2″·0	Double star at 18″. A double occultation of the smaller component observed by Innes, September 21, 1904.
τ Ceti	1 39·4	−16° 28′	3·7	1″·95	
Lacaille 661	2 6·4	−51° 19′	6·5	1″·9	
σ Draconis	19 32·6	+69° 29′	4·8	1″·9	
Auwers A.G.C. 4999	13 40·2	+18° 20′	9·0	1″·9	

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TABLE VII

STARS IN SWIFT LINEAR MOVEMENT

1. RADIAL VELOCITIES

Name of Star.	Mag.	Spectrum.	Velocity in miles per second. Recession signified by +, approach by −.	Remarks.
ϕ_2 Orionis .	4·4	Solar	+62	Measured by H. M. Reese (Lick Bulletin, No. 31).
μ Cassiopeiæ .	5·4	,,	−61	Campbell, *Astroph. Journ.* xiii. 98.
Groombridge 1830	6·6	,,	−59	,, ,,
θ Canis Majoris	4·2	Antarian†	+59	,, ,,
δ Leporis .	3·9	Solar	+59	,, ,,
η Cephei . .	4·0	,,	−54	,, ,, viii. 157.
ϵ Andromedæ .	4·5	,,	−52	,, ,, xiii. 96.
α Phœnicis .	2·4	,,	+48·5	Determined by Gill, 1908.
μ Sagittarii .	4·0	Helium	−48	Campbell, *loc. cit.* This is one of the few helium-stars known to be in rapid motion.
1 Pegasi . .	4·2	Probably solar	−48	Campbell, *loc. cit.*
ζ Herculis .	3·0	Solar	−44	Bélopolsky. Visual binary.
61 Cygni . .	6·1	,,	−34·5	,, Total velocity relative to sun = 51 miles (Young).
Aldebaran .	1·1	,,	+34	Vogel and Campbell.
Capella . .	0·2	,,	+21	H. C. Lord, *Astroph. Journ.* xxi. 315.
γ Leonis . .	2·3	,,	−20	H. C. Lord. Visual binary.
χ Draconis .	3·7	,,	+20	Spectroscopic binary (W. H. Wright).

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2. TANGENTIAL VELOCITIES

Name of Star.	Mag.	Parallax.	Velocity in miles per second.	Remarks.
Arcturus . .	0·2	0″·026	257	Radial velocity = −4 miles a second (Newall).
Lalande 15290 .	8·2	0″·028	206	
Groombridge 1830	6·6	0″·14	150	Total velocity in space 159 miles a second.
μ Cassiopeiæ .	5·4	0″·108	103	
A. Oe. 11677 .	9·0	0″·10	88	
Z.C. V^h. 243 .	8·5	0″·312	82	
Lacaille 2957 .	6·0	0″·064	78	
Lacaille 9352 .	7·1	0″·288	73	
o_2 Eridani .	4·5	0″·166	72	
Groombridge 1822	8·0	0″·028	71	
e Eridani . .	4·4	0″·149	61	
Lalande 21258 .	8·5	0″·238	54	
Σ 1561 . .	6·7	0″·038	50	
β Hydri . .	2·7	0″·134	49	
Bradley 3077 .	6·0	0″·138	44	
ξ Tucanæ . .	4·1	0″·138	43	
θ Ursæ Majoris	3·4	0″·078	41	A 13·5^m comes at 5″, shares its proper motion of 1″·12 (Burnham).
31 Aquilæ .	5·3	0″·068	41	
61 Cygni . .	6·1	0″·37	41	
α Gruis . .	2·1	0″·015	40	This star gives nearly 600 times the light of our sun. Helium spectrum.
Lalande 21185 .	7·5	0″·351	40	
Lalande 27298 .	7·5	0″·088	36	
Lalande 18115 .	7·5	0″·138	36	
Piazzi XIV^h 212	6·3	0″·167	35	
Lalande 19022 .	8·1	0″·068	35	
Pollux . .	1·2	0″·056	34	
Regulus . .	1·3	0″·024	33	
20 Leonis Minoris	5·6	0″·068	30	
β Comæ . .	4·5	0″·118	29	
Groombridge 34	7·9	0″·298	28	

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INDEX

Abbe, distribution of nebulæ, 357
Aberration of light, annual, 284, 311; secular, 311-312
Abipones, Pleiad-ancestry, 216
Abney, Sir William, total starlight, 7; photographic exposures, 23
Absorption, atmospheric, 21; in stars, 47, 50, 52, 57, 73, 136
Adams, detection of spectroscopic binaries, 192, 198, 222
Airy, Sir George, stellar parallax, 284; investigation of the sun's movement, 306, 307
Airy, Miss, discernment of twelve Pleiades, 218
Aitken, double satellite of Rigel, 195; elements of ϵ Hydræ, 197; revolution of a nebulous binary, 204
Alcor, companionship with Mizar, 201, 218, 328
Alcyone, spectrum, 59; modern conspicuousness, 217; leader of the Pleiades, 217, 218, 219, 222, 227; proper motion, 219, 220, 221; actual brilliancy, 221; adjacent nebulæ, 224, 225
Aldebaran, brightness, 3, 22; spectral type, 41, 45; colour, 51, 135, 140; satellite, 159; parallax, 297
Alexander, spiral theory of Milky Way, 343
Algol, a helium star, 87; eclipses, 117, 127-128; nature of system, 128-130; perturbations, 129, 132; parallax, 133; colour, 136
Algol variables, 82, 126; periods, 132; mean density, 133; distribution, 134; rapid binaries, 180; two-fold eclipses, 191
Al Sûfi, redness of Algol, 136; of α Hydræ, 136, 140; magnitude of θ Eridani, 180; brightness of the Pleiades, 217; notice of Andromeda nebula, 257
Altair, designation, 2; magnitude, 22; spectrum, 41; parallax, 297
America nebula, photographed by Wolf, 270; vicinity drained of stars, 352
Ames, hydrogen-lines in solar spectrum, 44
Anderson, discoveries of temporary stars, 90, 92; fading of θ Eridani, 180
Andromedæ, γ, colours, 145; triple system, 195, 255
Andromeda nebula, early observations, 10, 257; spectrum, 69-70, 260; star-blaze in, 88-89, 261; structure, 258-259; linked with the Milky Way, 259, 337; constitution, 260; oblique position, 260-261; intra-galactic, 350-351
Antares, third-type spectrum, 50; colour, 57, 137, 140; green satellite, 144, 145, 159
Antarian stars, 35, 50; chemistry, 50-51; variability, 54; non-galactic, 347, 370
Anthelmus, discovery of a temporary star, 85
Antliæ, S, character of light-change, 121, 125, 127
Antoniadi, view of a planetary nebula, 248
Apex, of the sun's way, indicated by stellar displacements, 303, 304, 308; by radial velocities, 310; assigned positions, 305, 306, 307, 308, 309
Aquilæ, η, a variable spectroscopic binary, 118
Aræ, R, an eclipsing star, 124, 126
Aræ, S, a cluster-variable, 120
Arcturus, ancient identification, 2; magnitude, 3, 22; spectral type, 41; titanium absorption, 45, 327; affinities, 51; thermal efficacy, 72, 74, 80; colour, 135, 136, 140; parallax, 297; linear velocity, 326
Argelander, star enumerations, 1, 6, 11, 346; identity of Tycho's Nova, 84; periodicity of Mira, 101; light-change of β Lyræ, 122; of S Cancri, 130;

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colour of Arcturus, 136; brightness of Pleione, 218; determination of the solar apex, 305; method of least squares, 306, 307; centre of solar orbit, 313; motion of 1830 Groombridge, 322
Arietis, γ, discovery as a double star, 150; slowness of revolutions, 158, 171; variability, 180
Arrhenius, luminosity of nebulæ, 280
Atlas, fluctuating brightness, 218; possible duplicity, 222
Aurigæ, β, a spectroscopic binary, 189
Aurigæ, ϵ, remarkable character of variability, 105, 192
Auwers, detection of Nova Scorpii, 88; orbits of Sirius and Procyon, 156, 157; star-parallaxes, 288, 291; reduction of Bradley's observations, 307

Bailey, discovery of cluster-variables, 118; their light-curves, 119; grouped in ω Centauri, 236
Baily, antique records of the Pleiades, 217; description of a star-cluster, 235
Ball, Sir Robert, parallax of Nova Cygni, 89; of 61 Cygni, 288; search for large parallaxes, 300
Balmer, law of hydrogen-series, 39
Barlow, description of σ Orionis, 203
Barnard, observations of Novæ, 86, 88, 95, 142; of cluster-variables, 119; stars within trapezium, 206; nebulæ in and around the Pleiades, 226; photographs of clusters, 228, 230; of nebulous stars, 241, 244; of diffused nebulosities, 271; of a perforated galactic cloud, 337; character of globular clusters, 240; discovery of a spiral nebula, 251; suggested movement of ring-nebula, 276; observation of a variable nebula, 277; parallax of 61 Cygni, 288
Bayer, nomenclature of stars, 8; designations, 99, 102, 196, 236; Andromeda nebula unnoticed by, 257
Bellatrix, silicon-absorption, 37; unmodified radiations, 46; absence of iron-lines from spectrum, 47
Bélopolsky, variable spectroscopic binaries, 118, 121, 131; unseen companion of Castor, 190; spectroscopic parallax, 286
Bessel, appreciation of Bradley, 12; disturbed motion of Sirius, 156; proper motion of 61 Cygni, 158; measures of the Pleiades, 219, 220, 221; investigations of stellar parallax, 284, 287-288, 289; detection of a partial system, 329
Betelgeux, designation, 2; magnitude, 22; spectrum, 51; colour, 57, 135, 136, 140; variability, 109; parallax, 297; light-power, 298
Binary stars, defined, 152. *See* Double Stars.
Birmingham, Catalogue of Red Stars, 55, 139; discovery of Nova Coronæ, 85; observations of red stars, 140, 141; their aggregation between Aquila and Cygnus, 142
Boeddicker, delineation of Milky Way, 337
Boltzmann, validity of Stefan's Law, 72
Bond, G. P., relative lustre of Sirius and the sun, 22; photography of double stars, 165; rifts in Andromeda nebula, 258-259; extent of the formation, 260; texture of Orion nebula, 265; catalogue of included stars, 268
Boraston, spectral characteristics of star-groups, 371
Boss, determination of solar apex, 307
Bouillaud, period of Mira, 99; notice of Andromeda nebula, 257
Boys, radiometrical experiments on star-heat, 73
Bradley, standard observations, 12, 307, 317; notices of double stars, 150; of Castor, 153, of 61 Cygni, 154, of γ Arietis, 158; stellar parallax, 283, 284; discovery of the aberration of light, 284
Brahe, Tycho, temporary star, 83-84; record of θ Orionis, 205; brightness of Alcyone, 217; Andromeda nebula ignored by, 257; stellar parallax, 282, 283
Brédikhine, parallax of Draco planetary, 247
Brisbane, magnitude of η Carinæ, 106; of α Centauri, 153
Bruce spectrograph, 33, 45, 321
Bruce telescope, 24
Brünnow, parallax of Draco planetary, 247; researches in stellar parallax, 292
Buffham, dark lanes in Hercules cluster, 238
Burchell, brightening of η Carinæ, 106
Burton, spectrum of Looped nebula, 69
Burnham, chromatic double stars, 145; rejection of wide pairs, 151; discoveries, 152, 169, 171, 181, 182, 195, 198, 203, 204; movements of 61 Cygni, 155; observation of Sirian satellite, 156; criticisms of stellar orbital computations, 168, 169, 200; quadruple stars, 203; constancy in light of trapezium stars, 205; close

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pairs in the Pleiades, 222; nebulous double star, 244; measures of Ring nebula, 276; variable nebula, 279

Calcium, in sun and stars, 42-44, 52, 53, 55
Campbell, hydrogen-lines in Mira, 53; in μ Centauri and γ Velorum, 61, 63; hydrogen-envelope of a star, 64; spectrum of Orion nebula, 68, 79; spectroscopic binaries discovered by, 121, 182, 192, 198; their proportionate number, 188; solar translation from stellar radial velocities, 310; import of result, 313; swiftness of faint stars, 321
Cancri, S, Algol-variable, 130; light-curve at minimum, 131
Cancri, ζ, colours, 147; quaternary system, 198-200
Cannon, Miss, discussion of stellar spectrograms, 29
Canopus, magnitude, 3; spectrum, 41, 44, 293; insensible parallax, 293, 297; real brilliancy, 293-294
Capella, apparent brightness, 3, 7; photometric rank, 22; spectral type, 41, 42, 44, 75; binary character, 44, 189; ultra-violet spectrum, 77; parallax, 190, 211; stage of development, 212
Carbon, in sun and stars, 42, 51, 54, 55
Carbon stars, 35; character of spectra, 54, 55; affinities, 56; number registered, 57
Carinæ, X, nature of light-change, 124, 125
Carinæ, η, spectrum, 62, 96, 109; light-changes, 106-108; situation, 269
Carrington, discernment of Pleiades, 218
Cassiopeiæ, B, 84. *See* Nova Cassiopeiæ
Cassiopeiæ, γ, gaseous spectrum, 59, 62, 87; variability of bright lines, 60
Cassiopeiæ, η, colours, 145; orbit, 156; masses and light-power of components, 175, 176, 210
Cassiopeiæ, μ, linear velocity, 326; spectral type, 327
Castor, spectrum, 41; a double star, 150; period of revolution, 153, 167; distant attendant, 159, 197; luminosity, 176; a double spectroscopic binary, 190; spectroscopic parallax, 190, 286
Celoria, double annular theory of Milky Way, 345; star-sounding, 364
Centauri, R^2, a short-period variable, 125
Centauri, α, magnitude, 3, 22; sun-like spectrum, 45; observed as a double star, 150; orbit, 153, 174; joint mass, 154; mass and luminosity of components, 175, 210; spectroscopic parallax, 187, 286; annual parallax, 287, 292; proper motion, 322
Centauri, μ, spectrogram showing bright lines, 60
Centauri, ω, variability of clustered components, 119, 120, 236, 237
Cephei, U, nature of eclipses, 131; time-inequalities, 132
Cephei, δ, short-period variable, 82, 117; a spectroscopic binary, 118; blue attendant, 145, 159
Cepheid variables, 117, 118
Ceraski, variability of U Cephei, 131
Ceraski, Madame, discovery of variable stars, 121
Chamberlin, origin of spiral nebulæ, 273
Chambers, catalogue of red stars, 139
Chandler, catalogue of variable stars, 97; periods, 99; relation to colour, 114; inequalities of Algol, 129; variations of Y Cygni, 132
Chase, parallax of Algol, 133; parallactic survey, 300
Cicero, colour of Sirius, 135
Clark, Alvan, relative lustre of Sirius and the sun, 22
Clark, Alvan G., Bruce telescope, 24; discovery of Sirian satellite, 156; stars within the trapezium, 206
Clusters, organic unity, 215, 233; mode of origin, 240; spectra, 241; crowded in Milky Way, 355
Clusters, globular, systemic constitution, 233-235; variability of component stars, 236-237; distribution of stars in, 234; variously organised, 238-239; non-nebulous, 240
Clusters, irregular, modes of conformation, 227-228; bifid and perforated, 229-230; diversified shapes, 231; no evidence of internal mobility, 232-233; nebular relations, 240, 241, 268, 359
Cluster-variables, 117, 118-121, 236-237; in Orion nebula, 268
Coal-sack in Milky Way, 336; photographed, 337; hypothesis in explanation, 347
Cocoon nebula, situated in a star-lacuna, 353
Colours, photographic effects, 26; of temporary stars, 84, 86, 87, 93, 95, 141-142; of lucid stars, 135-136, 138, 140; of double stars, 143-146, 160; alleged changes, 147-148; of nebulæ, 249, 264
Comas Solà, variability of trapezium-stars, 205
Common, photographs of nebulæ, 28, 31, 89, 252; nebulæ in the Pleiades, 224

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Comparison-spectra, use of, 17, 29, 36, 186
Comstock, relative masses of 85 Pegasi, 175; linear velocity of faint stars, 321
Copeland, spectrum of γ Velorum, 63; helium in Orion nebula, 67; spectrum of Nova Cygni, 87; map of adjacent stars, 88; spectrum of Nova Andromedæ, 90; observations of red stars, 140; of stellar nebulæ, 246
Copernicus, experiments in stellar parallax, 282
Cornu, hydrogen spectrum, 38; spectrum of Nova Cygni, 88
Coronæ, T, 86. *See* Nova Coronæ
Crommelin, immobility of a star, 330
Crucis, α, magnitude, 22; duplicity, 150; fixity of components, 158, 171; distant attendant, 159; corona of faint stars, 347
Crucis, β, an oxygen-star, 37; insensible parallax, 297
Crucis, κ, central in jewelled cluster, 232
Curtis, spectroscopic detection of an attendant on Castor, 190
Cygni, P, bright line spectrum, 62, 96, 109; triple increase of light, 85, 218
Cygni, UZ, an Algol-variable, 132-133
Cygni, Y, duplicate eclipses, 132, 191
Cygni, α, character of spectrum, 43, 46; insensible parallax, 297
Cygni, β, contrasted tints, 145; spectra of components, 148-149; discovery as a pair, 150; physical connection, 159; variability in light, 182
Cygni, χ, spectrum, 53, 104; light-changes, 102-103, 112
Cygni, 61, detection as a pair, 150; proper motion, 154, 158, 322; orbital relations, 155; parallax, 287-288, 298; luminosity, 289

Darquier, discovery of Ring nebula, 250
D'Arrest, observation of a red star, 141; conformation of "gold dust" cluster, 228; spectrum of a nebula, 245; proper motion of Draco planetary, 247; variable nebulæ, 277, 278, 279
Darwin, figures of equilibrium, 125, 209; earth-moon system, 208, 212
Davis, photographic parallax of 61 Cygni, 288
Dawes, double occultation of Antares, 144; colours of double stars, 147, 148; observation of 44 Boötis, 179
Dembowski, colours of double stars, 147, 148; observations of pairs variable in light, 180, 181
Democritus, stellar constitution of the Milky Way, 333
Denning, number of Pleiades seen by, 218
Deslandres, double-slit photography, 42; structure of fluted spectra, 50; δ Orionis a spectroscopic binary, 181; photograph of bi-annular planetary, 249; theory of spiral nebulæ, 273; luminosity of nebulæ, 280
De Thou, star-map showing Andromeda nebula, 257
Dewar, Sir James, luminosity at low temperatures, 281
Distance-ratio, of the stars, 295-296
Distances, of variable stars, 133-134; of the Pleiades, 221; of clusters, 238-239; of nebulæ, 247, 260, 356; of stars, 282-301; of the Milky Way, 346
Distribution, of stars in general, 19, 25, 363-365, 367, 369-371; of helium and Sirian stars, 37, 347, 370; of red stars, 56, 142; of gaseous stars, 64; of nebulæ and clusters, 65, 352-357, 358-359; of temporary and variable stars, 83, 90, 134
Doberck, computation of stellar orbits, 167, 168, 169, 179, 190
Döllen, principles of parallax determination, 292
Donner, photographic parallax survey, 300
Doppler, refrangibility of light altered by motion, 185
Double stars, colours, 143-146, 159-160; chromatic variability, 146-148; early recognitions, 150; definition, 151; dual systems, 152, 158-160; invisible attendants, 156; prospective research, 161; measurements, 162; computations, 163-165; photographic records, 165-167; orbital relations, 167-171, 173-174; masses, 170-175; luminosity, 176; eccentricity of paths, 177, 209; variability in light, 178-184; evolution, 209-211; proper motions, 322
Double nebulæ, numerous occurrence, 254; varieties, 255; relative fixity, 276
Downing, movements of the Hyades, 327
Draco planetary nebula, insensible parallax, 247; helical conformation, 248, 250; radial velocity, 275
Draper catalogue of stellar spectra, 24
Dreyer, observation of V Hydræ, 140; alleged changes in nebulæ, 276, 278
Dumb-bell nebula, indeterminate character, 255; analogous objects, 256, 351
Dunér, drawings of fourth-type spectra, 54; inequalities of Y Cygni, 132; observations of red stars, 140, 141; of double stars, 179, 182

Digitized by Google

Dunlop, observations of double stars, 153, 158
Durchmusterung, Bonn, 6, 7, 11, 86; photometric, 21; Cape Photographic, 26, 126, 322, 362, 365
Dyson and Thackeray, determination of the sun's apex from Sirian and solar stars, 308

Easton, isophotal curves in Milky Way, 337; spiral galaxy, 344, 345; relation of bright stars to galactic structures, 346; nebular distribution, 354
Eberhard, spectrographic study of χ Cygni, 54; movements within Orion nebula, 69; binary nature of ϵ Aurigæ, 105
Eberhard and Hartmann, origin of spark spectrum, 76
Ebert, anomalous dispersion in stellar atmospheres, 62
Eccentricity of stellar orbits, 170, 173, 177, 178, 195; evolutionary significance, 209
Eclipses, of variable stars, 118, 123, 125-133; duplicate, 125, 132
Edison, experiments on stellar heat, 73
Electra, fluctuating brightness, 218; real splendour, 221; nebulous connections, 224
Electrical conditions in stellar atmospheres, 41, 47-48, 75-76, 78; indicated by banded spectra, 49; in nebulæ, 79, 280
Elements of stellar orbits, 170, *note*
Elkin, heliometer employed by, 16, 294; measurements of the Pleiades, 220, 221; parallaxes of southern stars, 292-293, 297; of northern stars, 294, 297-298; mean parallax, 296, 307
Ellermann, cyanogen flutings in Antarian stars, 51; spectrographic investigation of carbon stars, 55
Elliptical nebulæ, 243, 257; foreshortening, 254, 260; examples, 257-261; rifted, 261-262
Engelmann, Nova Andromedæ, 89; colour of δ Cygni, 148
Enhanced lines, 41, 47, 76
Equatoreal telescope, described, 15
Equulei, δ, period of revolution, 168; spectroscopic parallax, 169, 187, 286; eccentricity of orbit, 177; optical companion, 201
Equulei, ϵ, triple system, 197
Eridani, o_2, mass and luminosity, 175, 176; triple system, 196; rapid motion, 293
Espin, detection of carbon stars, 57; spectrum of χ Cygni, 104; light-period of 63 Cygni, 108; variability of a red star, 110; of U Puppis, 181; Birmingham's Red Stars, 139; red stars in Perseus cluster, 232
Evershed, titanium in solar prominences, 45
Evolution, of stars, 36-37, 40-41, 46-47, 51, 56; conditioned by temperature, 77-78; of stellar systems, 208-214; of star clusters, 226, 240, 267
Extinctions, method of, 20

Fabricius, discovery of Mira Ceti, 99
Falb, shape of the visible universe, 374
Fallows, magnitude of η Carinæ, 106
Farley, colour of R Cephei, 110
Fenet, map of stars in Messier 11, 230
Feuillée, observation of α Centauri, 153
Finlay, magnitude of η Carinæ, 107
Fizeau, motion-shifts of spectral lines, 185
Flammarion, colours of 70 Ophiuchi, 147; variability of γ Arietis, 180; anomalous movement of ζ Cancri, 199; star system in Cygnus, 329
Flamsteed, star designations, 196, 201; aberrational shifting of the pole star, 283, 284
Fleming, Mrs., spectrographic discoveries, 29, 52, 57, 62, 64; of Novæ, 90, 92; of an eclipsing star, 132
Flint, researches in stellar parallax, 300
Fomalhaut, spectrum, 41; perspective movement, 304
Fowler, titanium-flutings in Antarian stars, 51
Franks, colours of 70 Ophiuchi, 147
Franz, parallax of Nova Andromedæ, 89
Fraunhofer, objective prism, 28; instrumental refinements, 286; Königsberg heliometer, 289
Frost, spectrogram of Nova Geminorum, 95; helium stars as close binaries, 189; radial motion of ζ Cancri, 200
Frost and Adams, spectrogram of Arcturus, 45; spectroscopic component of θ Orionis, 264; low velocities of helium stars, 321

Galileo, observation of Nova Serpentarii, 84; stellar parallax, 282; composition of the Milky Way, 333, 341
Gaseous stars, triple spectra, 58; first recognitions, 59; spectral variability, 60; nature of atmospheres, 61; effects in, of dispersion and anomalous refraction, 61-62; prismatic sweeps for, 64
Geminid variables, 117, 121, 125, 126
Geminorum, ζ, a spectroscopic binary, 121; disturbance of motion-curve, 192

Digitized by Google

Geminorum, η, long-period variable and spectroscopic binary, 181-182, 192, 197
Gill, Sir David, photographic registration of stars, 6; the sun's stellar magnitude, 22; a model solar star, 45; spectrum of η Carinæ, 62, 109; spectrogram of α Phœnicis, 186; photograph of 47 Toucani, 237; employment of the heliometer, 289; parallaxes of southern stars, 292-294, 297; average parallax, 294; rotation of bright stars, 331
Gilliss, colour of η Carinæ, 107
Glasenapp, computation of stellar orbits, 167
Goldschmidt, nebulous condition of Pleiades, 224
Goodricke, variability of β Lyræ, 122; eclipse theory of Algol, 127
Gore, the sun's stellar magnitude, 22; stellar orbits, 167, 182; aspect of 85 Pegasi, 171; mass-brightness of binaries, 176; estimated number of the stars, 363, 365
Gothard, spectrum of γ Cassiopeiæ, 60; photographs of nebulæ, 250, 253
Gould, Uranometry, 1; variability of R Normæ, 104; observations of red stars, 140, 141; photographic measurement of the Pleiades, 219; swift southern stars, 322; superposed galaxies, 347; belt of bright stars, 366
Groombridge, circumpolar catalogue, 308, 317
Groombridge, 1830, proper motion, 322; a runaway star, 325; spectral type, 327
Gully, record of Nova Andromedæ, 89
Guthnick, periodicity of Mira, 100, 101

Hahn, central star in ring nebula, 251
Hale, double-slit method in solar photography, 42; solar flocculi, 43; cyanogen in Antarian stars, 51; spectrographic investigation of carbon stars, 55; their affinities, 56; reversals in metallic spectra, 59
Hall, A., parallax of Nova Andromedæ, 89; catalogue of stars in Præsepe, 233
Hall, Maxwell, spread of Merope nebula, 224; elements of sidereal system, 368-369
Halley, observations of nebulæ, 10; of clusters, 230, 239; magnitude of η Carinæ, 106
Harding, bright and faint sections of ring nebula, 250
Hartwig, outburst of Nova Andromedæ, 89; eclipses of UZ Cygni, 132
Harvard Photometries, 21; spectrographic surveys, 28-29
Heis, star-enumeration, 1; high and low maxima of Mira, 100
Helical nebula, 248
Heliometer, Yale College, 220, 294, 300; adaptation to parallactic measures, 289, 298; Königsberg, 289, 291; Cape, 293
Helium, a terrestrial element, 36; absorption in stars, 37, 47; emission, 58; variable bright line, 60; low refractive power, 62; present in nebulæ, 67
Helium-stars, recent discrimination, 36; nebular affinities, 36, 46, 68, 270; absorptive features, 37; galactic condensation, 37, 347; enhanced spectral lines, 47; emissive spectra, 58, 60; as temporary apparitions, 96; as eclipse-variables, 133; as spectroscopic binaries, 189; remoteness, 299, 320; small linear velocities, 321; galactic condensation, 347
Helmert, catalogue of stars in M 11, 230
Henderson, parallax of α Centauri, 287
Henry, Paul and Prosper, photographic telescope, 25; photography of double stars, 166; of the Pleiades, 219; discovery of Pleiades nebulæ, 224
Hercules, cluster in, central condensation, 234; distribution and number of components, 238, 239; surmised distance, 240; spectrum, 241
Herculis, α, fluted spectrum, 52; variability in light, 109; green companion, 145, 176; their common proper motion, 159; spurious parallax, 292
Herculis, 95; colour change, 147; a physical pair, 159; relative fixity, 171
Herschel, Caroline, attendant to Andromeda nebula, 258, 259
Herschel, Sir John, stellar nomenclature, 1; outburst of η Carinæ, 107; redness of stars, 137, 143; colours of γ Leonis, 146; of 95 Herculis, 147; disturbed motion of 70 Ophiuchi, 155; revolutions of ζ Cancri, 199; nebulous double stars, 204; detection of sixth trapezium-star, 205; conformation of clusters, 229, 231, 235, 237; descriptions of clusters, 230, 236; measurement of jewelled cluster, 232; number and dynamical condition of globular clusters, 233-235; varieties of nebulæ, 245, 249, 251, 252, 261, 262; satellite-stars, 250, 276; Whirlpool nebula, 253; double nebula, 254; dumb-bell, 255; aspect of

Digitized by Google

Orion nebula, 264; nebula in Argo, 268, 279; Omega nebula, 269; light-change in nebulæ, 278, 280; stellar parallax, 288; systematic movements of stars, 331; the Milky Way in Argo, 335; galactic structure, 336, 338, 339, 342; nebular distribution, 353; galactic relations of a cluster, 359; number of the stars, 362; belt of bright stars, 366

Herschel, Sir William, observations of nebulæ, 11; planetary nebulæ, 65, 245, 249; maximum of Mira, 99; variability of α Herculis, 109; colours of stars, 137, 143, 145, 146, 147; discoveries of double stars, 151, 169, 196, 197, 198; period of Castor, 167; magnitudes of 44 Boötis, 179; double-treble star, 203; arrangement of stars in clusters, 229, 230, 236; cluster in Perseus, 231; components of Hercules cluster, 239; nebulous stars, 243, 244, 245; ring-nebulæ, 252; diffused nebulosities, 267, 270; Omega nebula, 269; comets and nebulæ, 272; variable nebulæ, 278, 279; investigation of the sun's movement, 304, 305, 306; systematic parallax, 313; structure of the Milky Way, 336, 338, 340; disc-theory, 340-341; "hole" in Scorpio, 342; replacement of stars by nebulæ, 352; construction of the heavens, 360; star-gauges, 364; inter-systematical stars, 370

Hevelius, designation of Mira Ceti, 99; record of R Cephei, 110; observation of θ Orionis, 205

Higgens, colour-change of 95 Herculis, 147

Hind, crimson tint of R Leporis, 57, 140; observations of effete Novæ, 84, 85; discovery of Nova Ophiuchi, 85; variations of S Cancri, 130; observation of a colour-variable, 141; detection of a variable nebula, 277

Hipparchus, star determinations, 12; new star, 82; cluster in Perseus, 231; no notice of Andromeda nebula, 257

Höffler, distance of star-system in Ursa Major, 328

Holden, study of Orion nebula, 28; colours of double stars, 144; stellar group in trifid nebula, 207; helical nebula, 248; structure of Saturn nebula, 250; stars in Orion nebula, 268; type-curve of nebulæ, 274; nebulous effects in Milky Way, 339; star patterns, 372

Holwarda, light-change of Mira, 99

Hooke, twinkling of stars, 4; duplicity of γ Arietis, 150; observation of fifth trapezium-star, 205; count of the Pleiades, 218

Hough, quaternary stellar systems, 203

Houzeau, visual enumeration of stars, 1; study of galactic luminosity, 337

Huggins, Lady, artificial star-patterns, 372

Huggins, Sir William, measurement of radial motion, 18, 29, 186; use of dry plates, 23; faintness of nebulæ, 27; spectrographic methods, 29; discovery of hydrogen-series in white stars, 38, 39, 40; spectrogram of Aldebaran, 45; spectra of Andromeda nebula, 70; of Nova Coronæ, 85; of Nova Andromedæ, 90; of Hercules cluster, 241; of Draco planetary, 247; experiments on stellar heat, 72; invention of reflecting slit, 148

Huggins, Sir William and Lady, Atlas of Stellar Spectra, 29; calcium in the sun, 44, 76; determination of chief nebular line, 65; spectra of Orion and Andromeda nebulæ, 67, 260, 264; ultra-violet stellar spectra, 77; spectrograms of β Cygni, 149; spectroscopic component of θ Orionis, 206; evolutionary effects of gravity, 211

Humboldt, first view of 47 Toucani, 237

Hussey, period and mass of δ Equulei, 168, 169; elements of the system, 177; spectroscopic parallax, 187, 286

Huygens, observation of θ Orionis, 150; delineation of Orion nebula, 264

Hyades, dissection into drifting groups, 327; reached by a galactic side-stream 337

Hydrogen, absorptive action in stars, 36, 37, 38, 40, 41, 42, 43, 44, 47, 56; in the sun, 44; cosmic, 37, 39, 47, 63; rhythmical spectral series, 38-39; emission in variables, 52-53, 79, 102, 104; in helium stars, 59, 60-61; in Wolf-Rayet stars, 63; in nebulæ, 66, 67, 79; in Novæ, 85, 87, 91, 95, 109; low refractivity, 62

Innes, investigation of variable stars, 104, 105, 120, 126; detection of quaternary systems, 202, 203, 330; variability of a nebula, 279; a swiftly moving star, 322

Iron, absorption in sun, 47; in Antarian and carbon stars, 52, 55; emission in Mira Ceti, 53

Irregular nebulæ, 243, 257, 270; capricious forms, 262-264, 269

Jacob, movements of 61 Cygni, 155; spurious parallax of α Herculis, 292

Digitized by Google

Jacoby, photographic comparisons of the Pleiades, 219
Janssen, double-slit method in photography, 42
Johnson, magnitude of η Carinæ, 106

Kaiser, colour-change of Arcturus, 136
Kapteyn, quality of galactic stars, 26; nebulosity round Nova Persei, 94; detection of variable stars, 126; meridian observations for stellar parallax, 298; parallax and magnitude, 299; treatment of proper motions, 308, 323; solar velocity, 309; distances and proper motions, 320, 321; a swift star, 322; mean stellar velocity, 324; solar cluster, 367
Kayser, wave-lengths of hydrogen-lines, 39
Kazwini, description of the Pleiades, 218
Keeler, photographic nebular survey, 11; photographs of nebulæ, 31; their chief spectral line, 65; their electrical glow, 79; prevalent spirality, 254, 344; their radial movements, 275; photograph of Hind's nebula, 277
Kelvin, Lord, gravitative power of the sidereal world, 325
Kepler, star of 1604, 83, 84; distance of the stars, 282, 285
Key-hole Nebula, the matrix of η Carinæ, 106, 209; conformation, 268-269; seeming change, 279
Kirch, variability of χ Cygni, 102; observation of M 11, 229
Kirchhoff's Law, 61
Klein, chromatic period of α Ursæ Majoris, 136; shape of sidereal world, 374
Klinkerfues, stellar variability, 111
Knorre, colour-perception, 137
Knott, variability of U Cygni, 183
Konkoly, spectral fluctuations of γ Cassiopeiæ, 60
Kövesligethy, colour-change of α Ursæ Majoris, 136
Krüger, catalogue of red stars, 139; parallaxes of rapidly-moving stars, 291

Lacaille, southern nebulæ, 10; magnitude of η Carinæ, 106; of α Centauri, 153; star catalogue, 317
Lalande, list of red stars, 138; notice of the Draco planetary, 247; stars observed by, 317
Lambert, Milky Way, 331
Lane, law of cooling for gaseous bodies, 77
Langenbach, temperature-relations of line-spectra, 79
Langley, multiple star in trifid nebula, 207
Laplace, dark stars, 156
Lassell, cluster in Gemini, 228; observations of nebulæ, 246, 249, 268
Lau and Wirtz, colour-change of α Ursæ Majoris, 136
Least squares, principle of, 305-306
Leavitt, Miss, detection of variable stars, 97, 268, 356
Le Gentil, attendant to Andromeda nebula, 258
Leowitz, apocryphal apparitions of Nova Cassiopeiæ, 84
Lewis, relative masses of binary stars, 175
Light-equation in stellar orbits, 129, 285
Light-pressure, effect on Nova Persei, 95
Light-ratio defined, 19
Lindauer, observation of Nova Cassiopeiæ, 84
Liveing and Dewar, temperature of electric spark, 76
Lockyer, Sir Norman, helium in stars, 36; enhanced lines, 41, 76; Antarian stars, 50; nebular spectrum, 65; ultra-violet stellar spectra, 75; temperatures of the stars, 78; variables regarded as binaries, 111, 184; constitution of Andromeda nebula, 260; cometary affinities of nebulæ, 272
Loewy, estimated number of charted stars, 363
Lohse, J. G., map of stars near Nova Cygni, 88
Lohse, O., elements of Sirian system, 156; investigation of cluster in Perseus, 232
Loomis, period attributed to η Carinæ, 107
Looped nebula, spectrum, 69, 263; aspect, 262-263
Ludendorff, periodicity of ϵ Aurigæ, 105, 193
Lunt, spectrogram of α Phœnicis, 136
Lyræ, β, variable bright lines in spectrum, 59, 60, 87; light-change, 82, 116, 122-123, 125; analogous objects, 123
Lyræ, ϵ, quadruple star, 201-202; origin, 214

McClean, distribution of helium stars, 36; oxygen in stars, 37, 64; spectrographic apparatus, 109
Mädler, disturbed circulation of 70 Ophiuchi, 155; hypothetical parallax, 172
Maestlin, observation of Nova Serpentarii, 84; discernment of Pleiades, 218
Magellanic clouds, Wolf-Rayet stars collected in, 64; variable stars, 119, 134,

Digitized by Google

356; systemic unity, 351-352, 357; nebular connections, 353; conditions of aggregation, 356; origin, 358
Magnesium, a constituent of stars, 38, 40, 52, 60; green fluting of, 65
Magnitude, of stars, 2-3, 19, 22
Maia, magnitude, 218; real brilliancy, 221; spectroscopic satellite, 222; attached nebulæ, 224, 225, 252
Main, parallax of 61 Cygni, 288; solar apex, 307
Mariotte, blue stars, 143
Marius, first telescopic observation of Andromeda nebula, 257
Markwick, maxima of Mira Ceti, 100
Mason and Smith, observations of the trifid nebula, 280
Mass-brightness, of binaries, 176
Masses, of binary stars, how determined, 170; results obtained, 171-172; relative, 172-175; conditions of ascertainment for spectroscopic pairs, 190-191
Maunder, galactic clustering, 336
Maurolycus, observations of Nova Cassiopeiæ, 84
Maury, Miss, discussion of stellar spectrograms, 29; evolutionary series, 37; composite spectra, 148; spectroscopic duplicity of β Aurigæ, 189
Mayer, C., colours of double stars, 143; detection of stellar couples, 150, 168, 195, 202
Mayer, Tobias, division of ζ Cancri, 198
Meadows, parallax of α Centauri, 287
Meridian photometer, principle of, 20
Merope, magnitude, 218; adjacent nebulæ, 223, 224, 225, 226, 255
Messier, observations of nebulæ, 10, 261, 269
Meteoritic hypothesis, 65, 111, 184
Michell, red stars, 138; number of the Pleiades, 218
Micrometer, described, 15
Milky Way, a collection of star-groups, 9, 340-341, 351; quality of light, 26, 347; concentration in, of helium stars, 37, 347; of carbon stars, 56; of Wolf-Rayet stars, 64; of gaseous nebulæ, 65, 356, 358, 359; of temporary stars, 83, 90; of short-period variables, 133-134; of clusters, 228, 231, 355, 358-359; unrelated to double-star orbits, 177; prolonged towards great nebulæ, 259, 359; structure, 268, 335-338, 373; influence upon sun's course, 312, 313; upon stellar proper motions, 331-332; aspect, 333; folk-lore, 334; track across the sky, 334-335; delineations, 337; irresolvability, 338-339; stratum-theory, 339-341; flat ring theory, 342; spiral theories, 343-344, 348; compound formation, 345, 347; distance, 346; relation to nebular distribution, 353-357; star-density in, 364, 365, 369-370
Minchin, measurement of stellar heat, 73
Mira Ceti, hydrogen-lines bright in, 52, 102; spectrographic investigations, 53-54, 102; a typical variable, 82, 99; periodicity, 99-102, 112; proper motion, 133, 183
Mitchel, division of ν Scorpii, 202
Mitchell, spectrum of Sirius, 38
Mizar (ζ Ursæ Majoris), the leader of Alcor, 201, 213, 328
Monck, mass-brightness of binaries, 175; remoteness of white stars, 299
Montigny, scintillation of the stars, 4, 6
Müller and Kempf, photometric observations, 21
Multiple stars, varieties of combination, 194-195, 197, 213; invisible components, 197-200; perspective attendants, 201; quaternary groups, 201-208; 214; nebulous relationships, 204-207; evolution, 208-214

Nebulæ, early observations, 10, 257; number, 11, 254; association with helium-stars, 36, 46; gaseous spectrum, 65-67, 245, 247, 256, 272; continuous, 67, 70, 253, 281; stratification, 68; species, 69, 243; temperature, 79, 280-281; structure, 242, 246, 254, 281, 344; colour, 249, 264; cometary affinities, 272-274, 276; seeming immobility, 275-276; radial velocities, 275, 358; variability in light, 277-280; tenuity, 280; intragalactic status, 349, 352-353, 355; stellar relations, 350, 352-353, 359; distribution, 353-357, 359; variety in constitution, 357
Nebulæ in the Pleiades, 223-226; forms, 274; drift through space, 275
Nebulium, a gaseous constituent of nebulæ, 65, 68, 245; spectrum, 66, 67; emission by temporary stars, 87, 92
Nebulosity, round Nova Persei, 93-95, 241; about the Pleiades, 226; diffused, 270-271
Nebulous stars, first notice of, 243; affinities, 244
Newall, spectrum of Nova Geminorum, 95
Newcomb, total light of the stars, 7; nature of the nebulosity round Nova Persei, 95; complexity of stellar systems, 199; proper motion of Alcyone, 219; investigation of solar motion, 309; average stellar velocities,

Digitized by Google

321, 324; runaway stellar speed, 325; star-drift in Ursa Major, 328; medial line of the Milky Way, 334; parallax of galactic stars, 346; range of galactic magnitudes, 347; distribution of stars, 365, 369
Newton's law, universal validity, 170
Nichols, heat of the stars, 73-74
Noël, observation of η Carinæ, 106; redness of γ Crucis, 140
Nova Andromedæ, outburst, 88, 261; spectrum, 89, 90; colour, 142; intra-galactic situation, 350-351
Nova Aurigæ, spectral relationships, 62, 91, 109; discovery, 90; nebular transformation, 91-92
Nova Cassiopeiæ, 83-84; colour-change, 141
Nova Centauri, 90
Nova Coronæ, 85-86; colour-change, 141
Nova Cygni, 86-88; colour-change, 142
Nova Geminorum, 95; colour, 142
Nova Persei, luminous fluctuations, 92-93; connected nebulosity, 93-95; colour-changes, 142

Olbers, period of χ Cygni, 103
Omega nebula, piecemeal discernment, 269; photograph, 270; suspected luminous changes, 279
Ophiuchi, 70, colour-change, 147; perturbed revolution, 155; masses and light-power of components, 175, 176, 210
Orbits of binary stars, apparent, 163-165, 167; actual, 163; number computed, 167, 169; methods of determining dimensions, 168; elements, 170, *note*; relative and separate of components, 173-174; eccentricity, 177
Orion nebula, isophotal contours, 27; photographs, 28, 265, 267; spectrum, 65, 67, 68; internal movements, 69, 276; variable stars in, 134, 268; "Fish-mouth" aspect, 242; flocculent texture, 264; plan of structure, 265-266; a developing cluster, 267, 350; recession from the sun, 275; steadfast light, 279; galactic connections, 337, 359; paucity of surrounding stars, 352
Orion stars, 36. *See* Helium-stars
Orionis, ϵ, spectrum, 36, 37, 40
Orionis, θ, early spectral type, 37, 68; shifting bright lines, 67-68; multiple character, 150; relation to surrounding nebula, 205, 264; successive detection of components, 205-206; genetic affinities, 213
Orionis, σ, multiple star, 148, 203
Orthochromatic plates, 28, 30, 50
Osthoff, redness of stars, 100
Oxford Uranometry, 20
Oxygen in stars, 37, 47, 64, 68; in the sun, 42, 49

Palmer, spectrogram of Nova Cygni, 87; spectroscopic parallax of α Centauri, 187; binary character of κ Pavonis, 192; components of Hercules cluster, 238, 239; nebular spectrum, 281
Parallax, annual, mode of determination, 14, 15, 286-287; photographic, 30, 298-300; of Novæ, 89, 94; of variable stars, 133; spectroscopic, 169, 187, 190, 285-286; hypothetical of binaries, 172; of the Pleiades, 221; of a nebula, 247; smallness, 282; associated effects, 283-284; by light-equation in stellar orbits, 285; results of measurements, 287-300; of galactic stars, 346
Parallax, secular, 303
Pegasi, 85, relative masses of components, 175; optical attendant, 201
Pegasi, κ, period, 169; spectroscopic and visual system, 201
Pegasi, U, analogy with β Lyræ, 123
Pernter, scintillation of Sirius, 5
Perrine, spectrogram of Nova Aurigæ, 92; spectrum and nebula of Nova Persei, 93
Perseus, double cluster in, 231-232; assumed centre of sun's orbit, 313; galactic relationship, 358
Personal equation, defined, 14; in double-star measurement, 165
Peters, C. A. F., stellar parallax, 290, 294
Phœnicis, α, radial velocity, 186
Photographic plates, 23, 28, 30, 50, 55; telescopes, 24-25, 30-31; International chart, 25, 363; irradiation, 25; stellar magnitudes, 26; catalogues, 362, 364, 365; star-gauging, 363
Photographs, of nebulæ, 28, 31, 93-94, 224-226, 251, 253, 256, 259-260, 263, 265, 267, 269, 270-271, 277; of stellar spectra, 29, 40, 41, 42, 43, 44, 45, 52, 53, 54, 60, 63, 186; of nebular spectra, 67, 70, 260; of double stars, 165-167; of the Pleiades, 219, 224-226; of various clusters, 228, 230, 232, 236, 241; of nebulous stars, 241, 244; in the Milky Way, 337, 347
Photography, employment in sidereal research, 22-26, 31-33; photometric, 25-27; spectroscopic, 28-29; radial motion determined by, 29, 186, 323; discoveries by, 29, 33, 52, 90, 92, 93-94, 97, 236, 268; stellar parallax by, 30, 298-299; rapidity and versatility, 32; investigation by, of nebulous

Digitized by Google

relationships, 207, 224, 242, 250-251, 254, 266-267
Photometer, polarising, 20; wedge, 20
Photometry, stellar, aim and scope, 19; methods, 20; results, 21-22; photographic, 25-27; nebular, 27
Photosphere, an essential feature of sun-like bodies, 34
Piazzi, star-catalogue, 317
Pickering, E. C., Harvard photometry, 20; atmospheric absorption, 21; sun's stellar magnitude, 22; sidereal photography, 24; distribution of the stars, 25; in the Milky Way, 369-370; stellar spectrograms, 36, 63; discovery of cosmic hydrogen, 37, 39, 66; sweeps for gaseous stars, 64, 66, 246; classification of variables, 82, 109, 116, 126; detection of spectroscopic binaries, 123, 189; investigation of Algol's eclipses, 127, 128; colours of 95 Herculis, 147; mass-brightness of binaries, 175, 201; the lost Pleiad, 218; paucity of true Pleiades, 220; their spectra, 223; counts of stars in globular clusters, 234; status of Looped nebula, 263; photographic catalogue, 364, 365
Pickering, W. H., nebular photometry, 27; photographic disclosure of great Snake nebula, 267
Pictor, flying star in, 322
Pigott, discovery of R Coronæ, 109
Planck, Stefan's law of radiation, 72
Planetary nebulæ, spectrum, 65, 66; structure, 66, 246, 256, 274; designated by Herschel, 245; specimens, 247-250; insensible parallax, 247, 300; radial velocities, 275
Plassmann, tidal theory of stellar variability, 111; secondary minimum of λ Tauri, 131; irregularities of U Cephei, 132; galactic inquiries, 345
Pleiades, mythological fame, 215-217; number visible, 218; common movement, 219-220; scale of system, 221-222; nebulous condition, 223-226, 350; a typical irregular cluster, 227, 267; forms of included nebulæ, 274; connection with the Milky Way, 337
Pleione, bright-line spectrum, 59; the lost Pleiad, 218
Plummer, estimates of star-light, 7; observations of Nova Cassiopeiæ, 84
Pogson, observation of Nova Scorpii, 88; periodicity of R Cephei, 108, 110
Poincaré, figures of rotating masses, 209
Pole-star, the "cynosure," 2; magnitude, 3, 22; standard brightness, 20; spectrum, 41; aberrational displacements, 283, 284
Pond, stellar parallax, 283, 284; secular aberration, 311
Position-angle of coupled stars, 163
Præsepe, measures of component stars, 233
Prey, relative masses of binary stars, 175
Pritchard, photometric investigations, 20; stellar parallax by photography, 30, 298; survey of the Pleiades, 220
Proctor, star-drift, 327-328; theory of Milky Way, 343; stellar outbursts in nebulæ, 350; nebular distribution, 353, 354; star-streams, 372
Procyon, magnitude, 22; spectral type, 41, 293; satellite, 157; luminosity, 158, 175; parallax, 297; proper motion, 322
Proper motions, defined, 14, 316; of variables, 133; of double stars, 154, 158, 160, 174, 322; disturbed, 156, 157, 158; of the Pleiades, 219, 220; a criterion of vicinity, 290-291, 317-318; common perspective element, 304, 308, 322-323; non-methodical character, 305, 314-315; ascertainment, 307, 308, 316-317; anomalies, 318-320; variation with spectral type, 321; swiftest known, 322; uncontrollable rates, 324-327; concerted, 327-330; surmised harmonies, 331-332
Ptolemy, star-magnitudes, 2; nebulosæ, 10; ignored η Carinæ, 106; magnitude of θ Eridani, 180; Pleiad-quartette, 217
Puppis, U, variable double star, 181
Puppis, V, supposed eclipses, 123
Puppis, ζ, cosmic hydrogen-lines in spectrum, 39

Radau, form of sidereal universe, 372
Radial motion, of stars, spectroscopically determined, 18, 185-186; variable, 66, 121, 128, 187, 192; of Novæ, 91, 93; in binary orbits, 285; indicative of solar translation, 310; of nebulæ, 275, 353
Radio-activity, cosmical effects, 80
Rancken, galactic rotation of stars, 332
Ranyard, structures in Orion nebula, 265, 266; tenuity of nebulæ, 280; composition of galactic clusters, 347
Red stars, spectral varieties, 49; strong self-absorption, 50, 52, 57, 140; catalogues, 55, 138, 139; variability in light, 110, 140; in colour, 141; examples, 140; distribution, 142; occurrence in pairs, 160; in Perseus cluster, 232; in galactic groupings, 371
Reflecting telescopes, advantages and

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drawbacks, 30-31; effects on star-colours, 138
Regulus, magnitude, 3; satellite, 145, 159
Respighi, prismatic effects of scintillation, 5; spectrum of γ Velorum, 63
Riccioli, division of ζ Ursæ Majoris, 150
Richaud, first observation of α Centauri, 150
Rigel, designation, 2; typical helium star, 37; spectrum unaffected by iron-absorption, 47; extent of ultra-violet radiations, 75; blue attendant, 145, 195; parallax, 297
Ring nebula, spectrum, 67; spiral conformation, 250, 251, 256; analogous objects, 251-252, 256; suspected movement, 276
Ritchey, nebula photographs, 31, 260; expansion of Nova Persei nebula, 94
Roberts, A. W., stellar eclipses, 123-126; mean density of Algol stars, 133; centre of gravity of α Centauri, 174; periodicity of κ Pavonis, 192
Roberts, Isaac, multiple exposures, 23; photographs of nebulæ, 31, 253, 256, 259, 261, 262, 265, 266, 270; of the Pleiades, 224; of various clusters, 230, 232, 238, 241; of a nebulous star, 244; of diffused nebulosities, 271; arrangement of stars in clusters, 229, 231; variable stars in Orion nebula, 268
Rosse, third Earl, colour of a star, 141; structure of star-clusters, 228, 230, 235, 238; ansæ of Saturn nebula, 250
Rosse, fourth Earl, double nebula, 254
Russell, H. C., measurement of cluster about κ Crucis, 232; change in Key-hole nebula, 279; photograph of the Coal-sack, 337; of stars in Crux, 347
Russell, H. N., tenuity of Algol variables, 133
Rutherfurd, photographs of the Pleiades, 219; of Præsepe, 233
Rydberg, principal series of hydrogen in stellar spectra, 37, 63

Sadler, double satellite of Rigel, 195
Safarik, identity of Nova Cassiopeiæ, 84; fluctuations of red stars, 110; uncertainties in colour-perception, 137
Safford, satellite of Sirius, 156; texture of Orion nebula, 265
Saturn nebula, colour, 249; ansæ, 250; radial velocity, 275
Savary, first computation of a stellar orbit, 169; parallaxes of binary stars, 285
Sawyer, minimum of R Coronæ, 110
Schaeberle, discovery of Procyon's companion, 157; helical nebula, 248; photographs of Ring and Dumb-bell nebulæ, 251, 256
Scheiner, spectrum of Capella, 44; rationale of bright-line stellar spectra, 61; spectrogram of Andromeda nebula, 70, 260
Schiaparelli, duplicity of ϵ Hydræ, 197; Merope nebula, 224
Schjellerup, catalogue of red stars, 55, 139, 140; observation of a colour-variable, 141
Schlesinger, parallaxes of faint stars, 299
Schmidt, discovery of Nova Cygni, 86; redness and periods of variable stars, 114; minimum of S Cancri, 130; colour of Algol, 136; history of Y Virginis, 181; nebular variability, 279
Schönfeld, record of T Coronæ, 86; colour of R Cephei, 110; observations of S Cancri, 130; variable nebula, 278; common drift of a star-pair, 329; proper motions referred to the Milky Way, 330
Schuler, notice of Tycho's star, 84
Schur, fixity of stars in Præsepe, 233; parallax of a comparison-star, 330
Schuster, dispersion-hypothesis of stellar bright lines, 61
Schwab, periodicity of Mira, 101
Scintillation, of white and red stars, 3-6; of Novæ, 4, 84
Scintillometer, 4
Scorpii, ν, a quaternary system, 202
Scorpii, ξ, a triple system, 197; complex mechanism, 213
Searle, nebulosity about Alcyone, 224
Secchi, objective prism, 28; stellar types, 35, 36, 49; carbon stars, 54, 55, 57; gaseous stars, 59; star-colours, 141, 143, 147, 148; vacuity in a cluster, 229; resolvability of a nebula, 249; vastness of interstellar space, 301; galactic cloudlet, 355; star-patterns, 371
See, ancient redness of Sirius, 135; disturbance of 70 Ophiuchi, 155; path of η Cassiopeiæ, 156; computation of stellar orbits, 163, 167, 197; eccentricities, 177; quintuple star, 195; tidal friction in stellar systems, 208, 209, 213
Seeliger, nebula round Nova Persei, 94; system of ζ Cancri, 200; galactic researches, 345, 365
Seneca, colour of Sirius, 135
Sidereal astronomy, conditions for prosecution, 12, 14, 31; methods, 13-14; availability of the camera, 22-23, 25, 31-33; insatiable of light, 33

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Sidereal physics, origin, 14; future progress, 16
Sidereal system, gravitative power, 325, 326; permanence, 330, 331; spectral relationships, 332, 370; finite dimensions, 361-362; organisation, 368-369, 371; comprehensive of stars and nebulæ, 373; primitive rotation, 374
Sidgreaves, spectrum of Nova Aurigæ, 91; of Nova Persei, 93
Silicon, in stars, 37, 41, 54; in the sun, 42
Sirian stars, 35, 40; nature of spectra, 37, 47, 48; photographic investigation, 38; hydrogen-absorption in, 38, 41; affinities, 46; absence of emissive symptoms, 58; light-variations, 117, 133; intense luminosity, 176; remoteness, 299, 320; small proper motions, 321; galactic condensation, 347, 370
Sirius, brightness, 3, 22; twinkling, 3, 5; spectrograms, 38, 40; hydrogen absorption, 41; ultra-violet spectrum, 75; ancient redness, 135; binary system, 156-157, 165; mass relations, 175; parallax, 293; proper motion, 322
Smyth, Admiral, discrimination of star colours, 137; tints of γ Leonis and 95 Herculis, 146, 147; cluster in Gemini, 228
Smyth, Piazzi, colour-change of 95 Herculis, 147
Solar stars, 35; relative numbers, 41; spectra, 42-45, 48; relationships, 46, 54, 56; bright lines absent from, 58; light-variations, 117; comparative vicinity, 299, 320; detached from galactic formations, 332, 347, 370
South, colours of double stars, 146, 147; observation of ζ Cancri, 198
Spectra, nebular, 65-70, 79, 245, 247, 253, 256, 260, 264, 281
Spectra, stellar, types, 35; of helium-stars, 36-37; of Sirian stars, 37-41; of solar stars, 41-45; fluted, 49-50; of Antarian stars, 50-54; of carbon-stars, 54-57; of gaseous stars, 58-61; of Wolf-Rayet stars, 62-63; of long-period variables, 52, 79, 102, 113; of short-period variables, 116; of temporary stars, 62; alterations in, 60; relations to temperature, 74-77, 78-79; of double stars, 148, 161, 179, 180, 181, 183, 210, 211; of the Pleiades, 223; of clusters, 241; connection with proper motion, 308
Spectrographic methods, 28-29, 33; application to stars, 38, 53-54, 55-56; to nebulæ, 66-67, 70, 260; to Novæ, 91
Spectroscopic binaries, discoveries, 66, 105, 118, 121, 128, 131, 189-192, 197, 203, 206-207, 222; relations to telescopic binaries, 168, 209; conditions of movement, 187-188; abundant occurrence, 188-189; mass determinations, 191; nebulous, 207, 270
Spectrum analysis, principles, 16; methods, 17-18; applied to the stars, 35
Spencer, distribution of nebulæ, 354
Spica, a spectroscopic binary, 190; mass of system, 191; parallax, 297
Spiral nebulæ, discovered at Parsonstown, 252; two-branched, 253; foreshortened into "spindles," 254; copious occurrence, 344
Star-drift, 327-328; characterises partial systems, 328-330
Stars, number visible, 1; designations, 1-2; magnitudes, 2-3; scintillation, 3-6; telescopic multitude, 6, 362; total light, 7-8, 361; individual study, 8, 16; combinations, 9; catalogues, 12, 317, 364; determination of places, 13; movements, 14, 303-304, 305, 308, 314, 316-332; parallaxes, 14, 15, 282-300; faintness of light, 17, 33; sun-like bodies, 34; spectral types, 35-57; gaseous, 58-65; chemistry, 37, 40-41, 47, 51-52, 55; temperatures, 71-80; eclipses, 125-133; colour-changes, 135-136, 141-142, 146-148; nature and variety of tints, 136-149; photographic charts, 363, 365; distribution, 363-365, 369-370; belt-formation, 366-368; collection into rings and streams, 371-373
Stebbins, spectrum of Mira, 53, 54; light-change, 100
Stefan's law of cooling, 71, 72
Stellar nebulæ, monochromatic light, 64; collected in Milky Way, 65; remoteness, 66, 246; radial velocity, 275
Stokes, Sir George, temperature-relations of line-spectra, 78
Stone, measurement of stellar heat, 72; centre of gravity of α Centauri, 174
Stratonoff, constitution of the Pleiades, 220; photographs of Pleiades nebulæ, 225; distribution of nebulæ, 354
Struve, F. G. W., observation of a red star, 141; colours of double stars, 143, 144, 147, 148, 182; assigned limit of apparent distance, 151, 159; detections, 164, 181, 197; observations, 198, 329; colour-perception, 146; magnitudes of 44 Boötis, 179; fifth star in trapezium, 205; stellar parallax, 284; criteria of stellar

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vicinity, 287; proper motions of double stars, 322; stratum-theory of Milky Way, 341; number of the stars, 363
Struve, L., determination of solar apex, 307; average proper motions, 318-319; their assumed rotation-component, 331
Struve, O., Pulkowa catalogue, 151; division of δ Equulei, 168; variable double stars, 178, 180; double satellite of γ Andromedæ, 195; movements of ζ Cancri, 199; detection of a variable nebula, 278
Stumpe, solar translation, 308
Sun, stellar magnitude, 22; machinery of radiation, 34; calcium-constituent, 42-43, 113; titanium, 45; temperature, 71, 80; analogy with variable stars, 112-114; relations to sidereal world, 301, 302-303; translation in space, 302-305, 306-310; nature of orbit, 311-313; possible companions, 330
Sun-spots, spectral analogies with red stars, 52, 56; cyclical variations compared with stellar light-changes, 112-114
Sutton, relations of star-belt, 366
Swift, nebulous star, 244; nebulous nebulæ, 247; hair-line nebulæ, 254; stellar and nebular couples, 255; detail in Omega nebula, 270

Tauri, λ, an eclipsing binary, 130-131
Tebbutt, fading of a red star, 141; variable double star, 180
Telescopes, equatoreal mounting, 15, 23; short focus, 24; photographic, 25; large apertures, 33, 138
Tempel, blaze in Andromeda nebula, 89; discovery of Merope nebula, 223
Temperature, of the sun, 71; of stars, 72-75, 77-78, 80; of nebulæ, 79, 280-281
Temporary stars, origin of spectra, 62, 91, 96; individual outbursts, 82-95; distribution, 83-90; sites of those extinct, 134; colour-changes, 141-142
Tenuity, of eclipsing stars, 133; of nebulæ, 280
Thiele, structure of fluted spectra, 50; period of Castor, 167
Thome, Cordoba Durchmusterung, 6
Tidal friction, influence on development of stellar systems, 208-209
Tisserand, theory of Algol's inequalities, 129, 132
Titanium, absorption-lines in solar and stellar spectra, 45, 52, 55; flutings in Antarian stars, 51
Toucani, 47, compressed cluster, 236; surrounding blankness of sky, 237
Trapezium, in Orion nebula, spectral peculiarities, 67-68, 264; discoveries of components, 205-206; genetic relations, 213; connected nebulous structures, 264
Trifid nebula, nuclear multiple star, 207; luminous changes, 279
Trowbridge and Richards, spectral flutings, 49
Turner, discovery of Nova Geminorum, 95; investigation of variable star periods, 113; relative drift of brighter stars, 332

Ursæ Majoris, α, colour-variability, 136
Ursæ Majoris, ζ, a telescopic double star, 150; a spectroscopic binary, 189, 197; quadruple system, 201; mode of origin, 213; part of a drifting squadron, 328
Ursæ Majoris, ξ, orbit, 169-170; relative masses of components, 175; a triple system, 197; lower limit of parallax, 285
Ursa Major, star-drift in, 327-329

Variable nebulæ, examples, 277-280
Variable stars, redness, 52, 114; display of bright lines at maximum, 52, 110, 113; third spectral type, 54; fourth type, 57; conditions of luminous excitement, 79; diversified phenomena, 81; five classes, 82; sudden apparitions, 82-96; catalogues, 97; of long periods, 97-105; irregular, 105-110; of short periods, 97, 116-126; distribution of periods, 98, 117; explanatory hypotheses, 110-115; eclipsing, 126-134; collected in groups, 134; coupled, 160, 178-184
Vega, apparent brilliancy, 3, 22; hydrogen-series in spectrum, 38, 41; temperature, 74; ultra-violet radiations, 77
Velorum, R^2, nature of eclipses, 126, 131
Velorum, S, eclipses undergone by, 126
Velorum, r, fading of colour, 141
Velorum, γ, emission-spectrum, 63, 87; oxygen-absorption, 64
Very, nebulosity round Nova Persei, 95
Villarceau, parallax of binaries, 285
Virginis, γ, duplicity, 150; orbit, 173-174; relative masses, 175; luminosity, 176; variability, 178; spectrum, 179; spectroscopic parallax, 286
Vogel, H. C., spectrographic measures of radial velocity, 29, 186, 323; discrimination of helium-stars, 36; movements within Orion nebula, 69,

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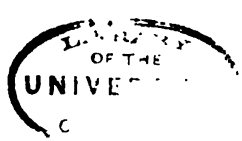
276; observation of Nova Coronæ, 86; spectroscopic binaries, 105, 190, 192; eclipses of Algol, 117, 128; spectra of 95 Herculis, 147; investigations of clusters, 232, 241; peculiarities of planetary nebulæ, 246, 249, 256; variable nebula, 278
Vogel, H. W., spectrum of hydrogen, 37

Ward, Nova Andromedæ, 89
Waters, distribution of nebulæ, 354
Webb, colour of U Cygni, 183; arrangement of clustering stars, 237, 238; planetary nebula, 300; star-patterns, 371
Weber, twinkling of stars, 6
Weersma, movements of the Hyades, 327
Wesley, photographs of the Pleiades, 225; diagrams of Andromeda and Orion nebulæ, 258, 259, 265
Whewell, interstellar situation of nebulæ, 351
Whirlpool nebula, typical of spiral class, 248, 252; deflection of branches, 253, 259; repulsive action betokened, 274
Wiedemann, luminescence, 77
Wien's law of spectral energy, 79
Williams, investigations of variable stars, 120
Wilsing, stellar spectrograms, 36; phase-curve of Algol, 129; perturbations of 61 Cygni, 155
Wilson, nebulosity round Nova Persei, 94; photograph of an irregular nebula, 263; repulsive effects in Whirlpool nebula, 274
Winlock, double satellite of Regulus, 159
Winnecke, light-change of S Monocerotis, 181; measurement of Præsepe, 233; variability of a nebula, 278; parallax of a faint star, 290
Wolf, C., catalogue of the Pleiades, 219, 220; nebulous condition, 224; map of stars in Præsepe, 233
Wolf, Max, discoveries of nebulæ, 11; observation of Andromeda nebula, 89; nebulosity round Nova Persei, 93; photographs of nebulæ, 253, 259, 270, 271, 352-353; "snake" nebula, 267; replacement of stars by nebulæ, 352-353; nebular survey, 354
Wolf, R., period attributed to η Carinæ, 107; solar and stellar periodicity, 112
Wolf-Rayet stars, emission beams, 56, 62-63; affinities, 56, 64, 95, 96; number and distribution, 64; insensible parallaxes, 300
Woods, detection of a variable star, 126
Wright, Thomas, disc-theory of Milky Way, 359
Wright, W. H., spectrograms of Mira, 53; spectroscopic parallax of α Centauri, 286

Yendell, colour and periods of variables, 114; eclipses of U Cephei, 131
Young, calcium-vapour in sun, 42, 43; diagram of sun's path in space, 312

Zach, red stars, 133
Zeeman effect imperceptible in fluted spectra, 49
Zodiac, signs of the, 2
Zöllner, polarising photometer, 21



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